UNITED STATES DEPARTMENT OF AGRICULTURE
Rural Electrification Administration

BULLETIN 1751H-601

SUBJECT: **Lightwave Fundamentals, Systems, and Application**

TO: All Telephone Borrowers
REA Telephone Staff

EFFECTIVE DATE: Date of Approval

EXPIRATION DATE: Three years from effective date

OFFICE OF PRIMARY INTEREST: Transmission Branch, Telecommunications Staff Division

PREVIOUS INSTRUCTIONS: This bulletin replaces the following Telecommunications Engineering and Construction Manual Sections:

TE&CM 970, Fundamentals of Lightwave Transmission
TE&CM 971, Lightwave Terminology
TE&CM 974, Lightwave Terminal Equipment
TE&CM 976, Lightwave System Application Guidelines

FILING INSTRUCTIONS: Discard the following Telecommunications Engineering and Construction Manual Sections:

TE&CM 970, Fundamentals of Lightwave Transmission
TE&CM 971, Lightwave Terminology
TE&CM 974, Lightwave Terminal Equipment
TE&CM 976, Lightwave System Application Guidelines

Replace with this bulletin.

PURPOSE: To provide information on various aspects of lightwave technology. This bulletin includes a basic description of the fundamentals of lightwave transmission, a description of various lightwave terminal equipment, and guidelines for the design of a lightwave system. All information in this bulletin is advisory.

George E Pratt

Acting Administrator

5/17/91

Date

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ABBREVIATIONS

ADM	Add-Drop Multiplexer
ANSI	American National Standards Institute
APD	Avalanche Photodiode
APS	Automatic Protection Switch(ing)
BER	Bit Error Rate
BIP	Bit Interleaved Parity
CCR	Customer Controlled Reconfiguration
DCC	Data Communications Channel
DCS	Digital Cross-Connect System
DLC	Digital Loop Carrier
EOC	Embedded Operation Channel
ILD	Injection Laser Diode
ISI	Inter-Symbol Interference
LED	Light Emitting Diode
MFD	Mode Field Diameter
NA	Numerical Aperture
OC	Optical Carrier
ODC	Optical Directional Coupler
OTDR	Optical Time Domain Reflectometer
OTS	Optical Transport System
PIN	Positive-Intrinsic-Negative
RST	Remote Switching Terminal
SONET	Synchronous Optical Network
SPE	Synchronous Payload Envelope
STS	Synchronous Transport Signal
TM	Terminal Multiplexer
VT	Virtual Tributary
WDM	Wavelength Division Multiplexer

DEFINITIONS

See Section 5 for definitions of various lightwave terms.

1. FUNDAMENTALS OF LIGHTWAVE TRANSMISSION

1.1 General

1.1.1 This section provides REA borrowers and other interested parties with an introduction to the fundamentals of lightwave transmission.

1.1.2 Although this section provides detailed descriptions of many lightwave terms and concepts, the reader should refer to Section 5 for definitions of any unfamiliar terms.

1.2 Advantages of Lightwave Transmission

1.2.1 Man has used light as a communications medium for many years. Examples are Paul Revere's lanterns, lighthouses, and ships' semaphore signaling. However, it has only been in recent years with the advent of optical fibers that lightwave communications has begun to reach its ultimate potential. Fiber optic or lightwave transmission is the sending of information via light rays over thin fibers of glass at high speeds.

1.2.2 There are many advantages in using fiber rather than the traditional twisted copper pairs. These include larger bandwidth, less signal loss over longer distances, immunity from lightning strikes, no electromagnetic or radio frequency interference, lighter weight, smaller size, and increased transmission security. The following paragraphs describe these benefits further.

1.2.2.1 Fiber is capable of providing more than 100 times the bandwidth of copper pairs. The bit rate of the terminal equipment not the fiber itself limits the bandwidth.

1.2.2.2 The low attenuation of fiber permits long nonrepeatered links as opposed to equivalent length copper cable systems that would require many repeaters and inherent additional cost and maintenance.

1.2.2.3 Since light, rather than electricity, transmits the information, neither lightning nor ground potential differences affect the transmission. (The use of fiber cables with metallic shields and strength members, however, may affect protection considerations.)

1.2.2.4 The small size and weight of optical fibers are generally advantageous in ease and economics of installation, for example, where duct space is at a premium and for longer unspliced plowing runs.

1.2.2.5 Since optical transmission produces no signal radiation, lightwave systems provide increased security.

1.2.3 Table 1-1 summarizes the benefits of fiber compared with copper. The table assumes the use of all dielectric fiberoptic cable.

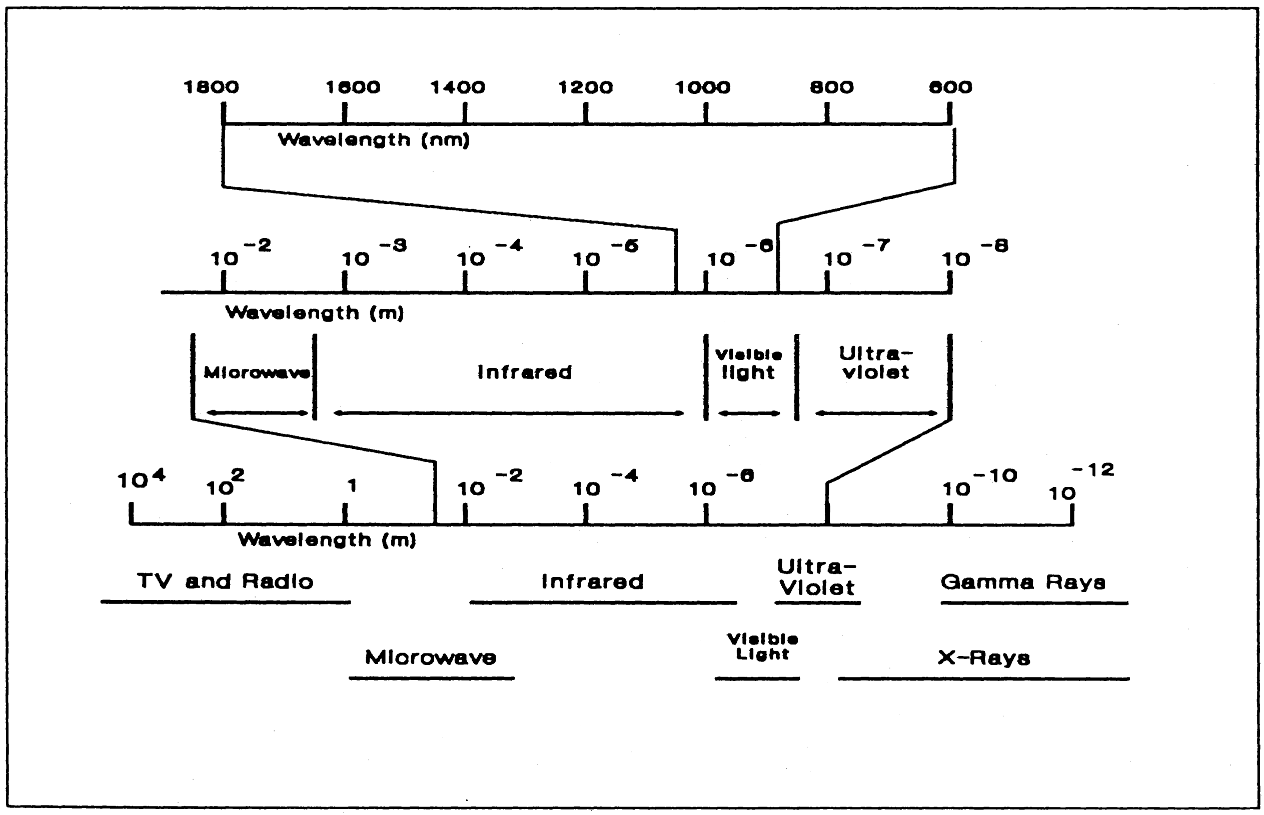
TABLE 1-1
BENEFITS OF FIBER OVER COPPER

Benefit	Copper	Fiber
RFI/EMI/Noise Immunity	No	Yes
Total Electrical Isolation	No	Yes
High Transmission Security	No	Yes
No Crosstalk	No	Yes
No Spark/Fire Hazard	No	Yes
High EMP Immunity	No	Yes
No Short Circuit Loading	No	Yes
Small Size	No	Yes
Light Weight	No	Yes

1.3 Introduction to Light and Lightwave Systems

1.3.1 In common usage, light is the visible portion of the electromagnetic spectrum. This covers the range of wavelengths from 400 to 700 nanometers (nm). When used in fiber optic communications, the lightwave spectrum generally includes any wavelength within the range of 600 to 1800 nanometers. Figure 1-1 illustrates this.

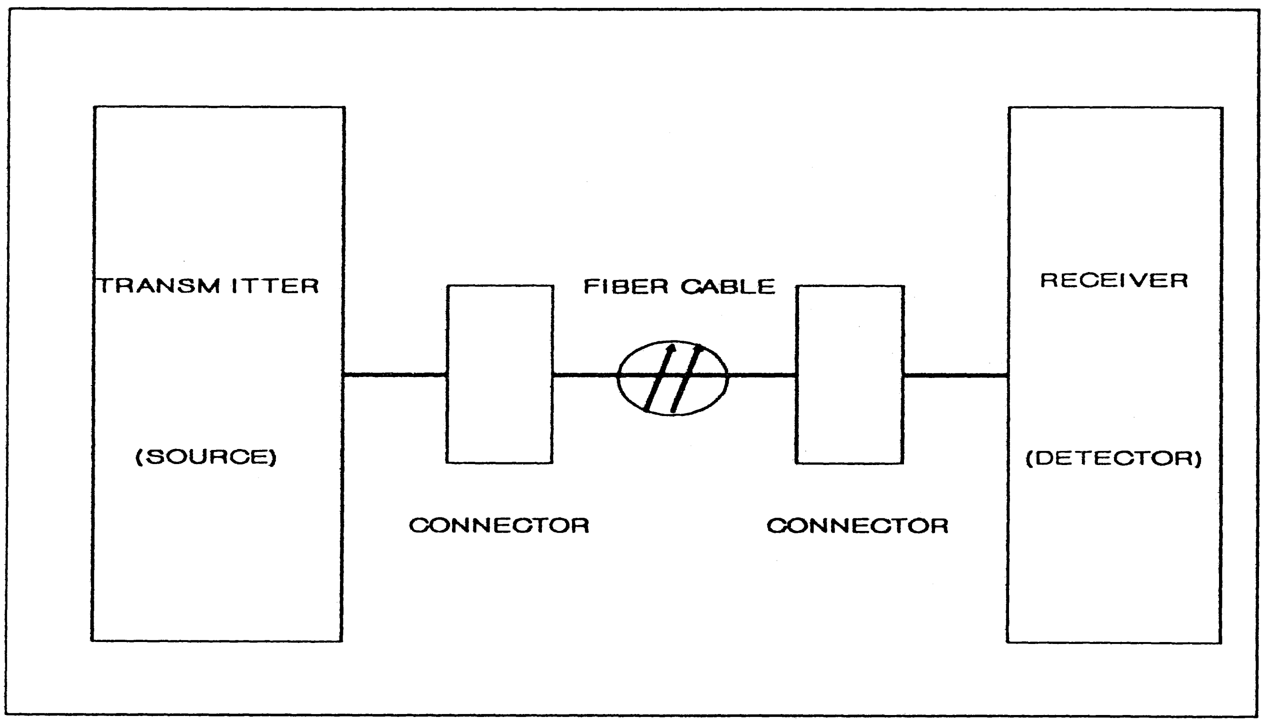
FIGURE 1-1
LIGHTWAVE SPECTRUM



1.3.2 In lightwave transmission, an optical source couples energy within this spectrum into an optical fiber. An optical receiver detects the propagated energy at the far end. For voice and data transmission, a lightwave terminal normally modulates the lightwave energy with intelligence using digital techniques. A lightwave terminal at the receive end of the fiber optic link also uses digital techniques to recover the intelligence.

1.3.3 A lightwave transmission system generally consists of a modulated signal source (transmitter) that inserts the lightwave energy at one end of the fiber link and an optical detector (receiver) and demodulator that receives the transmitted signal at the far end of the link and restores the applied intelligence to its original form. Figure 1-2 illustrates this basic arrangement.

FIGURE 1-2
BASIC LIGHTWAVE LINK



1.3.4 As with any transmission system, the lightwave signal is subject to transmission losses and distortion as it propagates through the optical fiber. This will be described in detail in later paragraphs.

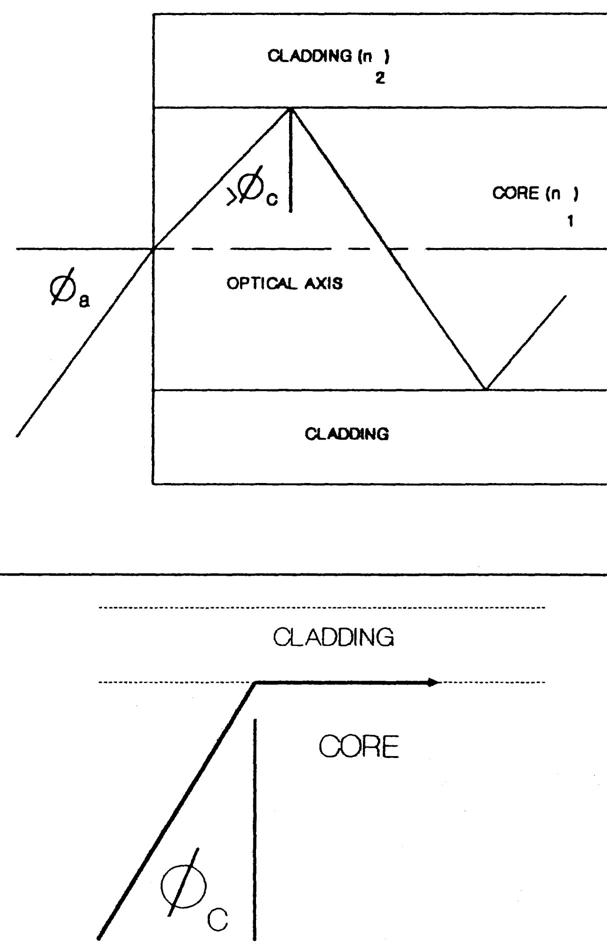
1.4 <u>Basic Optical Principles</u>

1.4.1 The following paragraphs discuss various aspects of the propagation of light and various properties of optical fiber. Although single mode fiber has largely replaced multimode as the facility of choice in telephony, this section discusses multimode fiber and its characteristics to provide a complete description of the topic of lightwave transmission.

1.4.2 An optical fiber consists of a central core of silica glass surrounded by another layer of glass, called the cladding, which has properties different from the core. In particular, the refractive indices of the core and the cladding are different. The ratio of the speed of light in a vacuum to the speed of light in a given material is the refractive index of the material.

1.4.3 Figure 1-3 illustrates the propagation of light through a step index multimode optical fiber. Figure 1-3 also shows the critical angle ϕ_c which is the minimum incidence angle for which total reflection occurs within the optical fiber. Therefore, any light ray striking the core-cladding interface at an angle greater than ϕ_c will be totally reflected into the core as shown in the lower box of Figure 1-3.

FIGURE 1-3
LIGHT PROPAGATION THROUGH OPTICAL FIBER



ϕ_c = Critical Angle
ϕ_a = Acceptance Angle
$\sin \phi_a$ = Numerical Aperture
n_1 = Refractive Index of the Core
n_2 = Refractive Index of the Cladding

1.4.3.1 The critical angle is the angle whose sine is the ratio of the refractive index of the cladding (n_2) to the refractive index of the core (n_1) [$\sin \phi_c = n_2/n_1$].

1.4.4 The Numerical Aperture (N. A.) defines the acceptance angle (ϕ_a) of light rays entering the fiber that will be totally reflected in the core. Trigonometrically, the Numerical Aperture is the sine of the incident angle at the fiber boundary which will produce total reflection at the core-cladding interface. See Figure 1-3. Mathematically, the N. A. is equal to the square root of the difference of the squares of the refractive indices of the core and the cladding, i. e., N. A. = $(n_1^2 - n_2^2)^{1/2}$.

1.4.5 As an example, assume an optical fiber consists of a core whose refractive index (n_1) is 1.60 and a cladding with a refractive index (n_2) of 1.54. (These numbers are arbitrary and used for illustration only.) Using the previously defined formula, N. A. = $(n_1^2 - n_2^2)^{1/2}$ = 0.43. Since the acceptance angle (ϕ_a) is the angle whose sine is N. A., ϕ_a in this example is approximately 26°. In other words, any light ray striking the end of the fiber at an angle between 0° and 26° around the optical axis will be totally reflected at the core-cladding interface as shown in Figure 1-3. In addition, for this same fiber the critical angle ϕ_c can be calculated as approximately 74° ($\phi_c = \sin^{-1} n_2/n_1$).

1.4.6 After the lightwave terminal has coupled the light into an optical fiber, some light rays travel along the optical axis whereas the core-cladding boundary reflects others as shown in Figure 1-3. The cladding absorbs other rays. The Numerical Aperture and the critical angle generally determine these paths as discussed in previous paragraphs. Each path that a light ray takes while traveling through an optical fiber is a propagation mode. The reflected modes that travel a farther distance than those propagated along the axis take longer to traverse the fiber length.

1.4.7 In order to place intelligence onto the light, the lightwave terminal modulates the beam of light entering the optical fiber. For illustrative purposes, the simple modulation technique of turning the light source on and off will be discussed. The source turns all the light rays (modes) off and on at the same time. However, since different modes of light take longer to travel from one end of the fiber to the other, the receiver senses each mode at a different time. Therefore, an "on" pulse of duration X transmitted by the source will have a longer duration as received at the far end. This pulse broadening is a form of distortion commonly known as modal dispersion. Figure 1-4 shows a simplistic view of modal dispersion.

1.4.8 In a lightwave transmission system the presence of modal dispersion makes the error-free detection of pulses more difficult. The received pulses are not only broadened but also distorted and rounded off. Figure 1-5 illustrates the effects of modal dispersion. The left side of Figure 1-5 shows the undistorted transmitted pulses. It can be seen that it would be rather simple to detect the pulses even if the bit rate were high. The right side of the figure shows the effect of modal dispersion on the bit stream. It can be readily seen that it is much more difficult to determine whether a pulse exists or not because of the overlapping of pulses. This phenomenon is intersymbol interference which causes higher pulse detection errors resulting in a higher bit error rate (BER).

FIGURE 1-4
MODAL DISPERSION

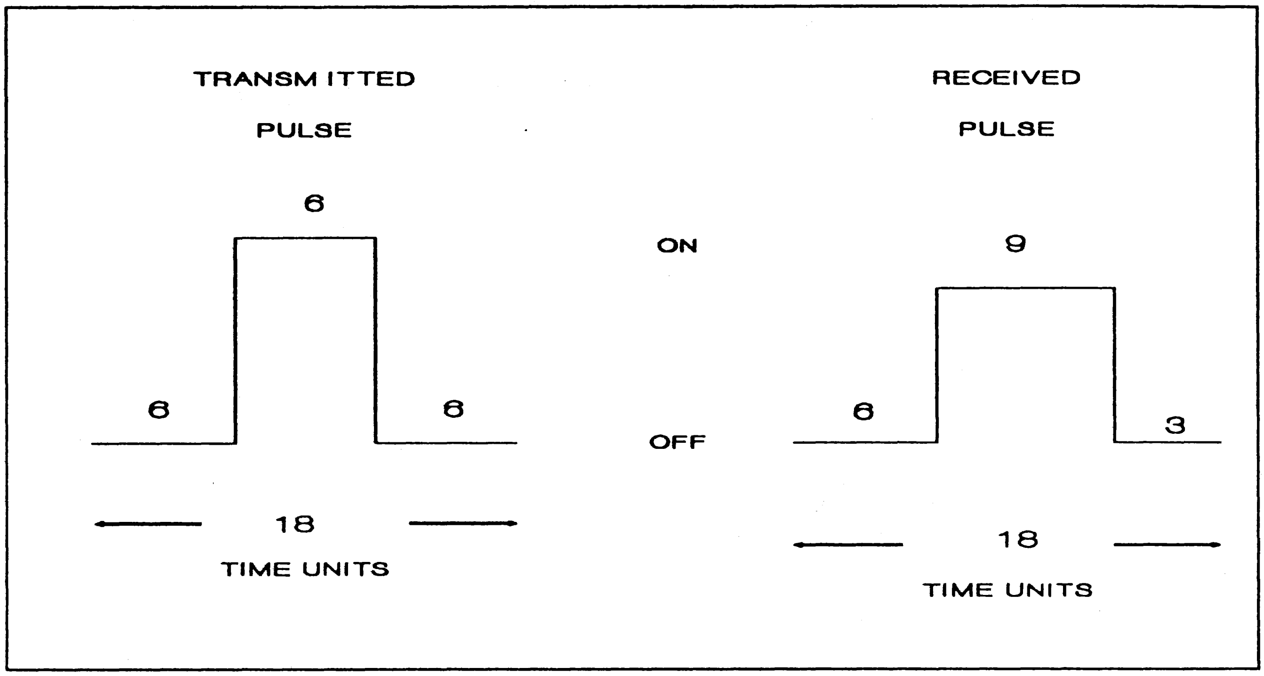
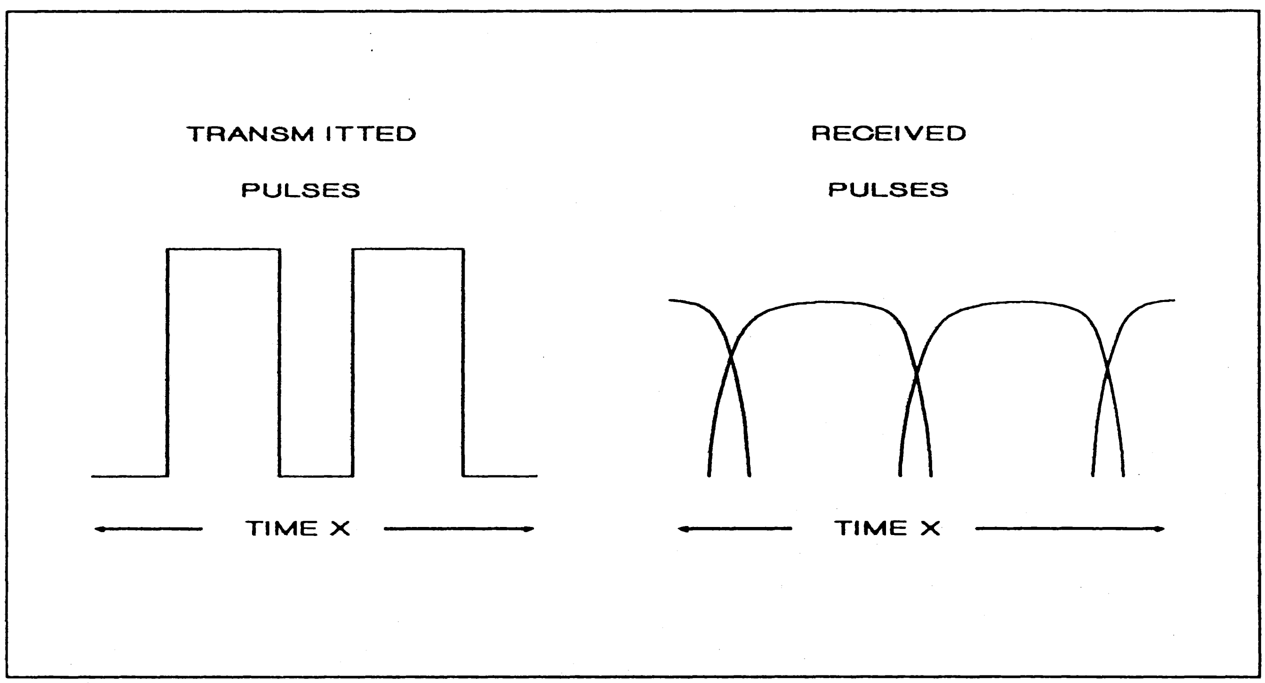


FIGURE 1-5
INTERSYMBOL INTERFERENCE



1.4.9 As the transmission distance increases, the effect of modal dispersion becomes more pronounced. Additionally, higher transmission rates produce an increased modal dispersion. Figures 1-6a and 1-6b illustrate this problem.

FIGURE 1-6A
LOW BIT RATE EFFECT ON MODAL DISPERSION

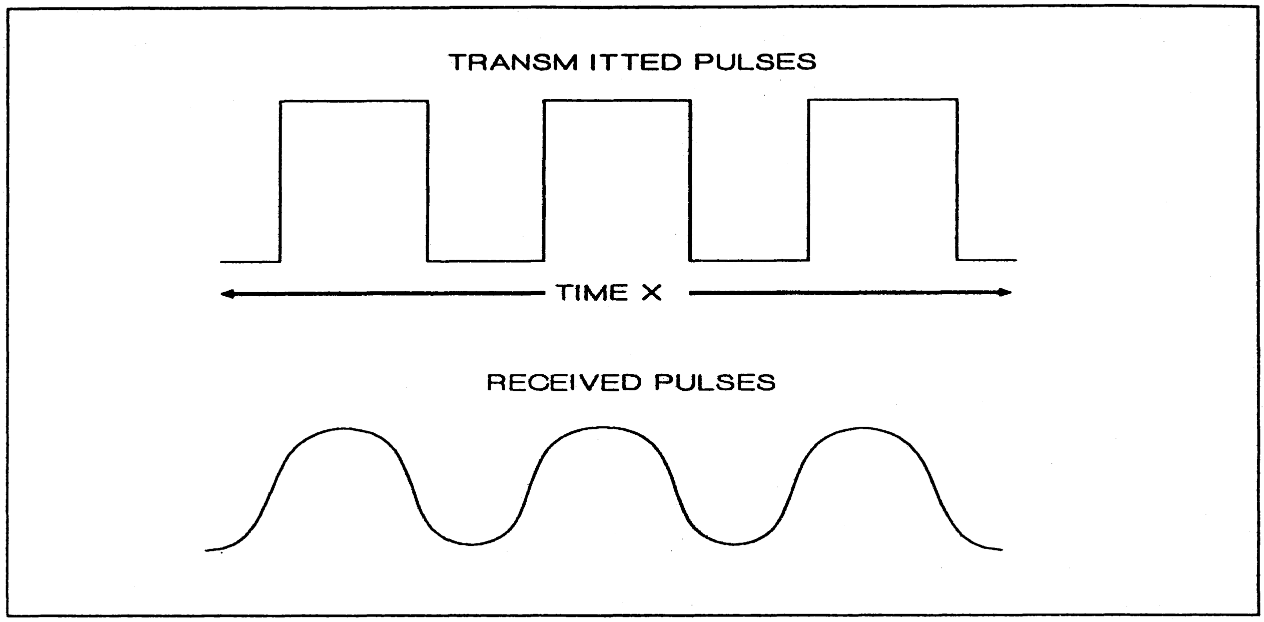
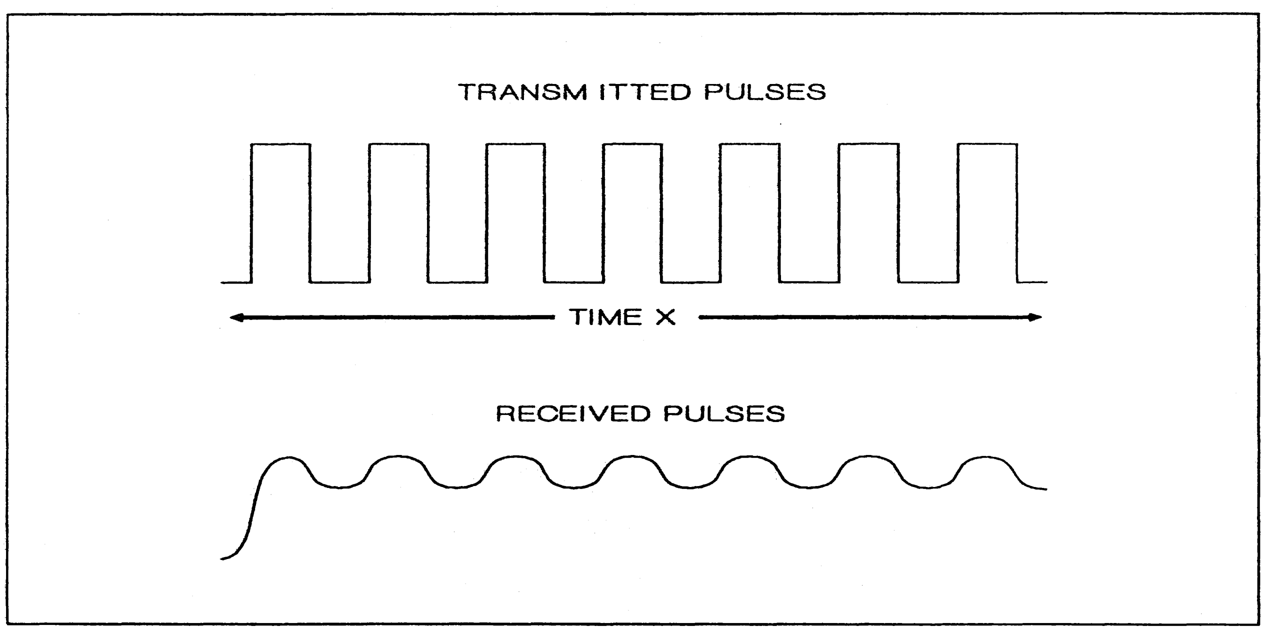


FIGURE 1-6B
HIGH BIT RATE EFFECT ON MODAL DISPERSION



1.4.10 Various factors associated with the fabrication and characteristics of optical fibers produce attenuation of the light as it propagates through the fiber. Any impurities in the fiber will tend to absorb the light. Additionally, the reflection of light at the core-cladding boundary is not total. The cladding absorbs a certain amount of the light. The amount absorbed is dependent upon the angle of incidence with the boundary. The amount absorbed increases as the incidence angle approaches the critical angle. This absorption produces attenuation of the light signal.

1.4.11 Physical irregularities in the optical fiber cause light to be absorbed and scattered also producing attenuation. These irregularities can be small or large bends or cracks. These problems can be minimized by special care during manufacture and by careful handling during installation.

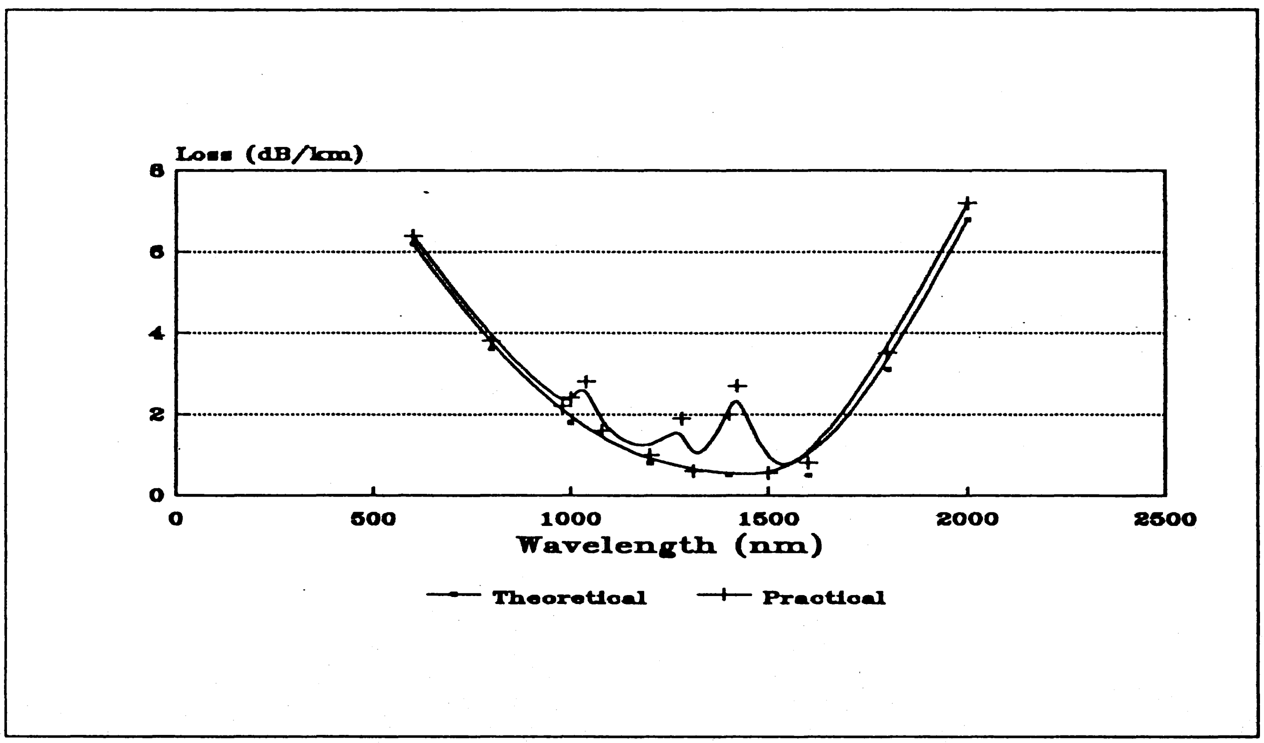
1.4.12 The attenuation (A) of light in an optical fiber is wavelength dependent and can be calculated as follows:

$$A\ (dB) = -10 \log P_o/P_i$$

where P_o = output power at the operating wavelength and
P_i = input power at the operating wavelength.

1.4.13 Figure 1-7 illustrates the relationship of attenuation and wavelength. The figure shows both the theoretical and practical attenuation. The scattering of light caused by the intrinsic structure of the fiber produces this attenuation. The practical attenuation shows loss peaks at certain frequencies caused by light absorption by impurities in the fiber. The figure shows exaggerated peaks for illustrative purposes. Today's fibers are much less prone to impurities than those of earlier years and the attenuation characteristics more closely resemble the theoretical curve shown in Figure 1-7.

FIGURE 1-7
ATTENUATION VS WAVELENGTH



1.4.14 The attenuation of an optical fiber is most often specified as a loss per unit length, typically dB per kilometer.

1.5 Characteristics of Optical Fibers

1.5.1 Generally, two optical fiber types are available: single mode and multimode. Today's telecommunications applications use single mode fiber almost exclusively. However, data communications use multimode fiber extensively.

1.5.2 Suppliers have manufactured two basic forms of Multimode fiber : step index and graded index. The step index fiber has a core with a uniform refractive index. The refractive index of this type of optical fiber changes (steps) only at the core-cladding boundary. As previously described, a step index multimode fiber supports propagation of many modes of light producing a significant modal dispersion.

1.5.3 Modal dispersion can be reduced by using graded index fiber. This multimode fiber has a core whose refractive index decreases radially outward from the optical axis. In graded index multimode fiber, light spirals within rings around the core axis from one end of the fiber to the other. Light in the outer rings travels faster than that in the inner rings. This minimizes modal dispersion.

1.5.4 In recent years a more common method of reducing modal dispersion has been the use of single mode fiber. A single mode fiber has a small diameter core. This construction limits the propagation of all modes except the one traveling along the optical axis. By definition, a single mode fiber is a step index fiber because of the uniform refractive index of the core. Since a single mode fiber supports propagation of only a single mode of light, modal dispersion is seldom a factor.

1.5.5 For single mode fiber, the term Numerical Aperture has little meaning since the only rays coupled into the fiber are those along the optical axis. Mode Field Diameter (MFD) or "spot size" defines the cross-sectional area of a single mode fiber that is available to couple lightwave energy in an optical fiber efficiently. The MFD is generally somewhat larger than the core diameter. In fact, approximately 30% of the lightwave energy propagates longitudinally through the cladding.

1.5.6 Although modal dispersion is generally not a problem in single mode fibers, other types of dispersion can affect lightwave transmission.

1.5.7 Waveguide dispersion occurs as a result of lightwave energy propagating through both the core and the cladding of single mode fibers. Since the core and the cladding are dissimilar materials with different refractive indices, light travels at different speeds in each material which causes a pulse broadening effect (dispersion) at the fiber output. Waveguide dispersion is wavelength dependent as shown in Figure 1-8 which illustrates a typical curve for an optical fiber.

1.5.8 Another form of dispersion occurs because different wavelengths of light travel at different speeds even through a material with a constant refractive index. Although single mode fiber allows only one mode of propagation, the lightwave energy consists of a range of wavelengths since most light sources radiate a band of wavelengths around a center wavelength.

This band defines the spectral width of the source. The fact that these various wavelengths travel at different speeds causes a broadening of the input pulses at the fiber output. This is material dispersion. Figure 1-9 depicts the relationship between material dispersion and wavelength for a typical optical fiber.

1.5.9 Most current lightwave transmission systems operate at 1310 nm or 1550 nm because the attenuation at these wavelengths is low as shown in Figure 1-7. Generally, especially in rural applications, attenuation is the limiting factor in how far a nonrepeatered light signal can be transmitted through a single mode optical fiber. Section 4 details the method for designing lightwave links. The attenuation at 1550 nm is less than at 1310 nm. It would, therefore, seem possible to engineer longer links at the longer wavelength. This is true to a point, however, wavelength dispersion can become a limiting factor at longer wavelengths.

FIGURE 1-8
WAVEGUIDE DISPERSION

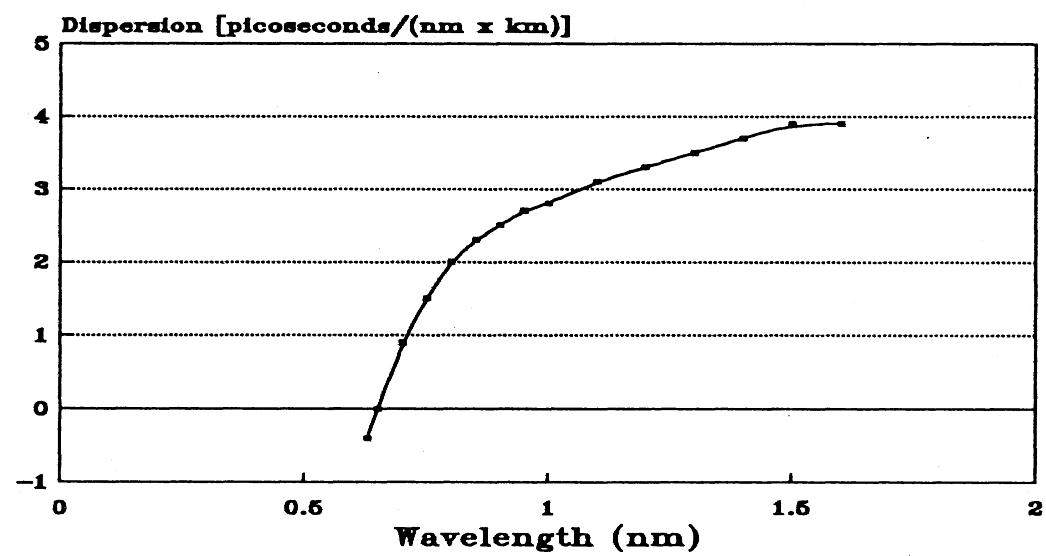
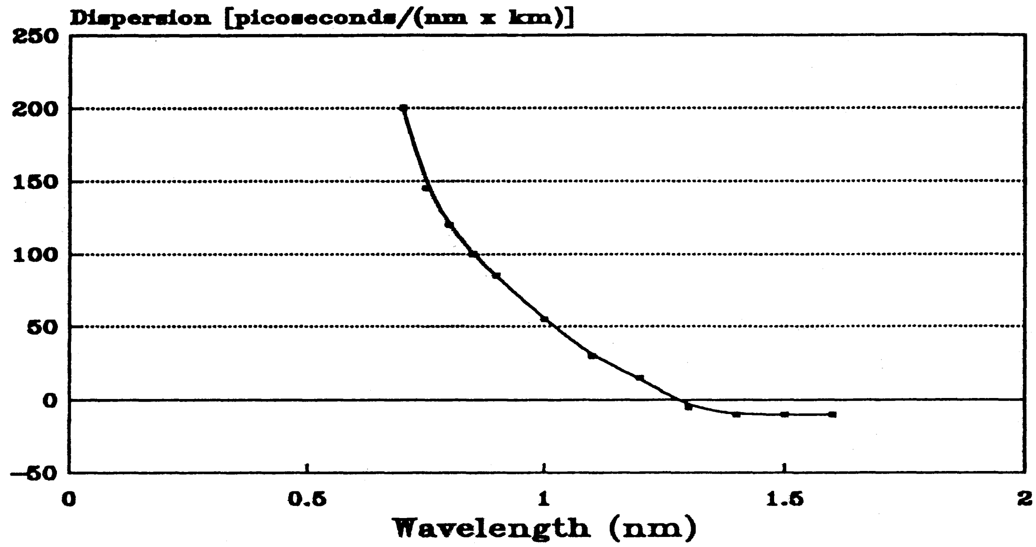


FIGURE 1-9
MATERIAL DISPERSION



1.5.10 As Figure 1-9 illustrates, material dispersion is approximately zero at 1310 nm. Since the information carrying capacity (bandwidth) of the fiber is inversely proportional to the dispersion, the bandwidth becomes very large at 1310 nm. On the other hand, at 1550 nm the material dispersion is much higher. This dispersion can be reduced by using a laser with a narrow spectral width. However, such lasers are quite expensive.

1.5.11 An alternative is to change the characteristics of the fiber. This can be done because the chromatic (wavelength) dispersion is the sum of the material dispersion and the waveguide dispersion. It is possible for these two dispersions to be opposite in sign and therefore their sum can be less than the magnitude of either, even zero at 1310 nm.

1.5.12 Since material dispersion is dependent on the chemical characteristics of the glass and difficult to change, manufacturers generally alter the waveguide dispersion by changing the fiber's refractive index. To make 1550 nm the zero dispersion wavelength, manufacturers fabricate the fiber such that the waveguide dispersion cancels out the material dispersion. This is dispersion-shifted fiber.

1.5.13 Another factor that must be considered in lightwave system design is the cutoff wavelength which is dependent upon both attenuation and dispersion. In actuality, a single mode fiber can support a second mode of light at shorter wavelengths. The cutoff wavelength is the longest wavelength at which the second mode can be transmitted.

1.5.14 Dispersion can be greatly increased if the system transmits the second mode since modal dispersion becomes a factor. The single mode fiber becomes a multimode fiber at wavelengths shorter than the cutoff wavelength. It is, therefore, important that the lightwave system operate at a wavelength greater than the cutoff wavelength.

1.5.15 The cutoff wavelength, although mostly determined by the fiber design, can be greatly affected by any bends in the fiber. If the cutoff wavelength is too low, bends may cause significant extra attenuation at wavelengths longer than 1310 nm. Therefore, it is important that the cutoff wavelength be long enough, e.g., 1100 nm, so that the attenuation at 1550 nm is low. If this is the case, the system could operate at either 1310 or 1550 nm.

1.6 Bandwidth Considerations

1.6.1 The bandwidth of a lightwave transmission system is the range of frequencies over which the system is capable of transmitting and receiving data. As a tighter definition, the usable bandwidth is the range of frequencies received at an amplitude no less than 3 dB below the amplitude of the signal at the center of the bandwidth.

1.6.2 Optical fiber specifications may list the usable bandwidth in terms of MHz x km. However, for single mode fibers it is more useful to describe bandwidth in terms of dispersion, i.e., picoseconds per nanometer-kilometer [ps/(nm x km)]. This factor describes the rise time of a light pulse which has passed through one kilometer of fiber.

1.6.3 The precise relationship between bandwidth and dispersion is somewhat complex. The following formula, however, gives a reasonable approximation.

$$\text{Bandwidth (MHz)} = 440 \times 10^3/(D \times LW \times L)$$

where:

D = the chromatic dispersion in picoseconds/(nm x km) at the operating wavelength
LW = spectral width in nm of the source
L = length in km of the link

1.6.4 It can be seen from the above formula that the bandwidth is inversely proportional to the chromatic dispersion, the spectral width and the link length. That is, as any of these factors increases in magnitude, the usable bandwidth of the lightwave system decreases.

1.6.5 As an example, assume that a system exists with a chromatic dispersion of 3.5 ps/(nm x km) and a spectral width of 2 nm. Figure 1-10 depicts the usable bandwidth over a range of link lengths for several values of chromatic dispersion. This figure shows that the usable bandwidth decreases with increasing link length. However, with the dispersion and spectral width used in this example, at a link length of 100 kilometers, the usable bandwidth exceeds 600 MHz.

1.6.5.1 If the dispersion in this example increases to 5.0 ps/(nm x km), the usable bandwidth would decrease to approximately 440 MHz. An increase to 10 ps/(nm x km) decreases the bandwidth to about 220 MHz.

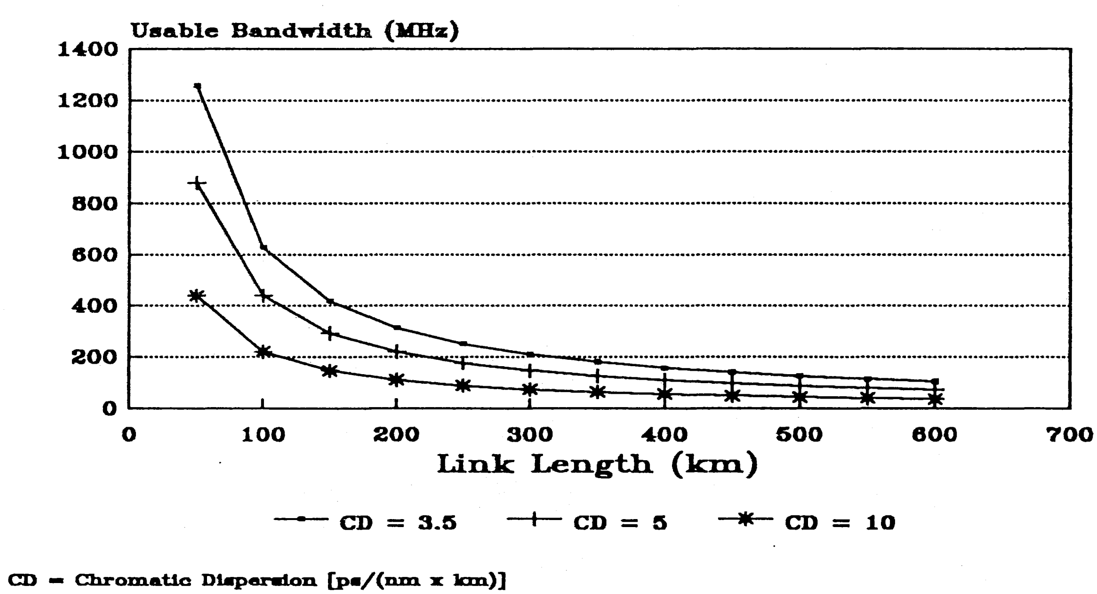
1.6.6 Figure 1-11 illustrates the relationship between usable bandwidth and chromatic dispersion. As the dispersion increases, the usable bandwidth decreases. Figure 1-11 assumes that the link length is 100 km and the spectral width is 2 nm.

1.6.6.1 Increasing the spectral width in the previous example (D = 3.5, L = 100) to 5 nanometers would cause the usable bandwidth to be decreased to about 250 MHz. An increase to 10 nm decreases the bandwidth to about 125 MHz.

1.6.7 Figure 1-12 shows the relationship between the spectral width of the source and the usable bandwidth. Similar to link length and chromatic dispersion, the usable bandwidth decreases with increasing spectral width. In Figure 1-12 the link length is 100 km and the chromatic dispersions are 3.5, 5, and 10 ps/(nm x km).

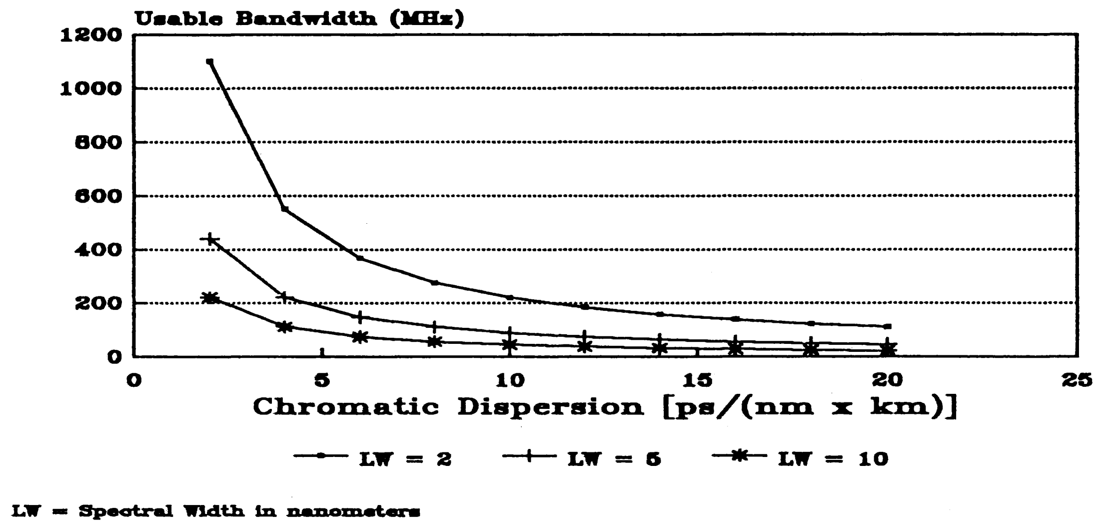
1.6.8 Although in theory the bandwidth of a lightwave system is approximately 90% of its optical bit rate, for practical purposes the bandwidth can be assumed to be equal to the bit rate.

FIGURE 1-10
BANDWIDTH VS LINK LENGTH



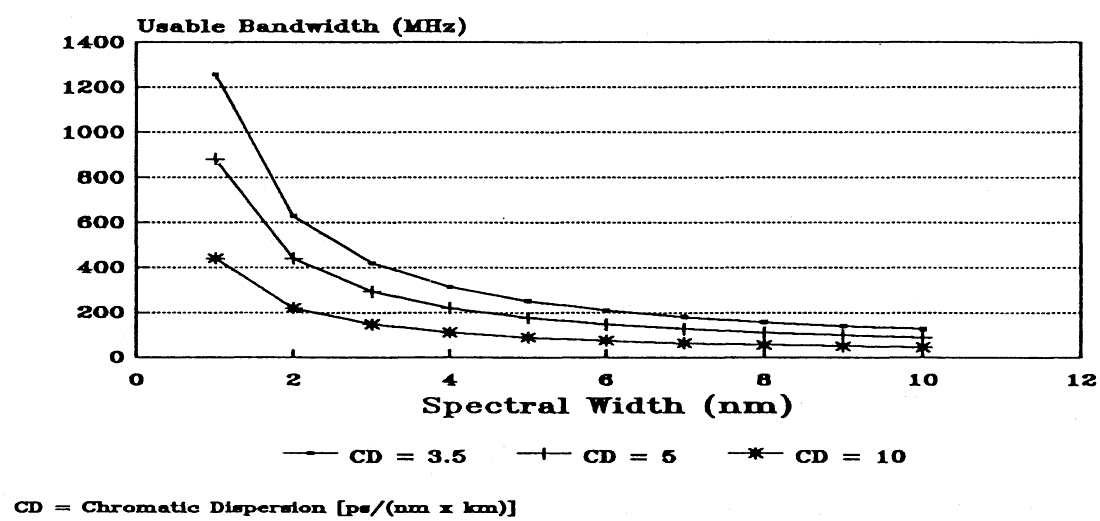
Spectral Width = 2 nanometers

FIGURE 1-11
BANDWIDTH VS CHROMATIC DISPERSION



Link Length = 100 km

FIGURE 1-12
BANDWIDTH VS SPECTRAL WIDTH



Link Length = 100 km

1.7 <u>Lightwave Transmission Systems</u>

1.7.1 Section 3 contains a detailed description of lightwave transmission systems and their components, e.g., transmitters and receivers.

1.7.2 Lightwave systems Accepted and Listed by REA include systems with optical bit rates in the range of 45 to 180 Mb/s. Telcos also may use systems with lower and higher rates where the situation warrants. Lightwave transmission systems include three basic types as described below.

1.7.2.1 The stand-alone multiplexer that can be configured either as an electrical multiplexer or as a lightwave transmission system simply by providing the appropriate cards.

1.7.2.2 The integral multiplexer that interfaces DS1, DS1C and DS2 level inputs and multiplexes them into one or more DS3 lightwave outputs.

1.7.2.3 The lightwave transport system that interfaces one or more DS3 inputs and provides one or more DS3 lightwave outputs. With this type of system, interface to DS1 level signals requires an M13 stand-alone multiplexer.

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2. LIGHTWAVE TERMINAL EQUIPMENT

2.1 General

2.1.1 This section provides REA borrowers and other interested parties with a detailed description of lightwave terminal equipment. Besides the overall terminal equipment descriptions, this section discusses individual components such as transmitters and receivers. This section also describes various applications and configurations to give the reader a comprehensive understanding of the topic.

2.1.2 Although this section provides detailed descriptions of many lightwave terms and concepts, the reader should refer to Section 5 for definitions of any unfamiliar terms.

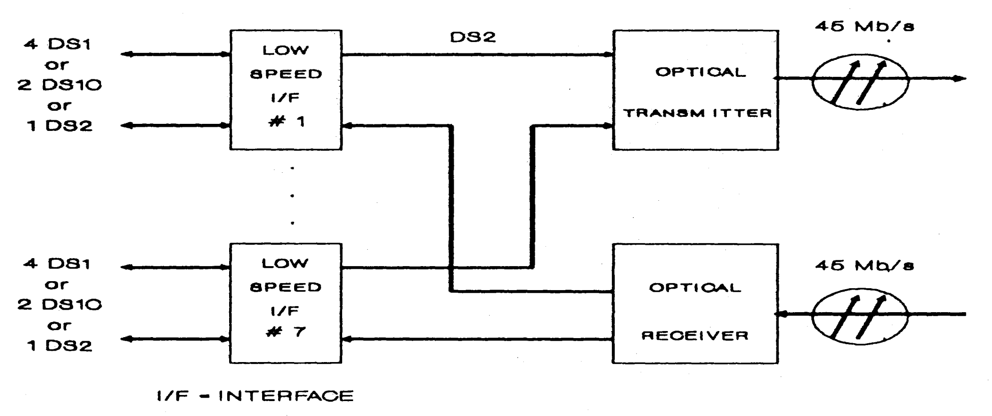
2.2 Basic Lightwave Terminals

2.2.1 Lightwave transmission terminals in general use today fall into three main categories.

Digital Multiplexer with Lightwave Transmission Capability
Lightwave Transmission System with Integral Multiplexer
Lightwave Transport System

2.2.2 Figure 3-1 shows a block diagram of a digital multiplexer configured as a lightwave transmission system. To form an electrical multiplexer, the optical transmitter and receiver can be replaced with an electrical to electrical multiplexer that combines the DS2 electrical signals into a DS3 electrical signal.

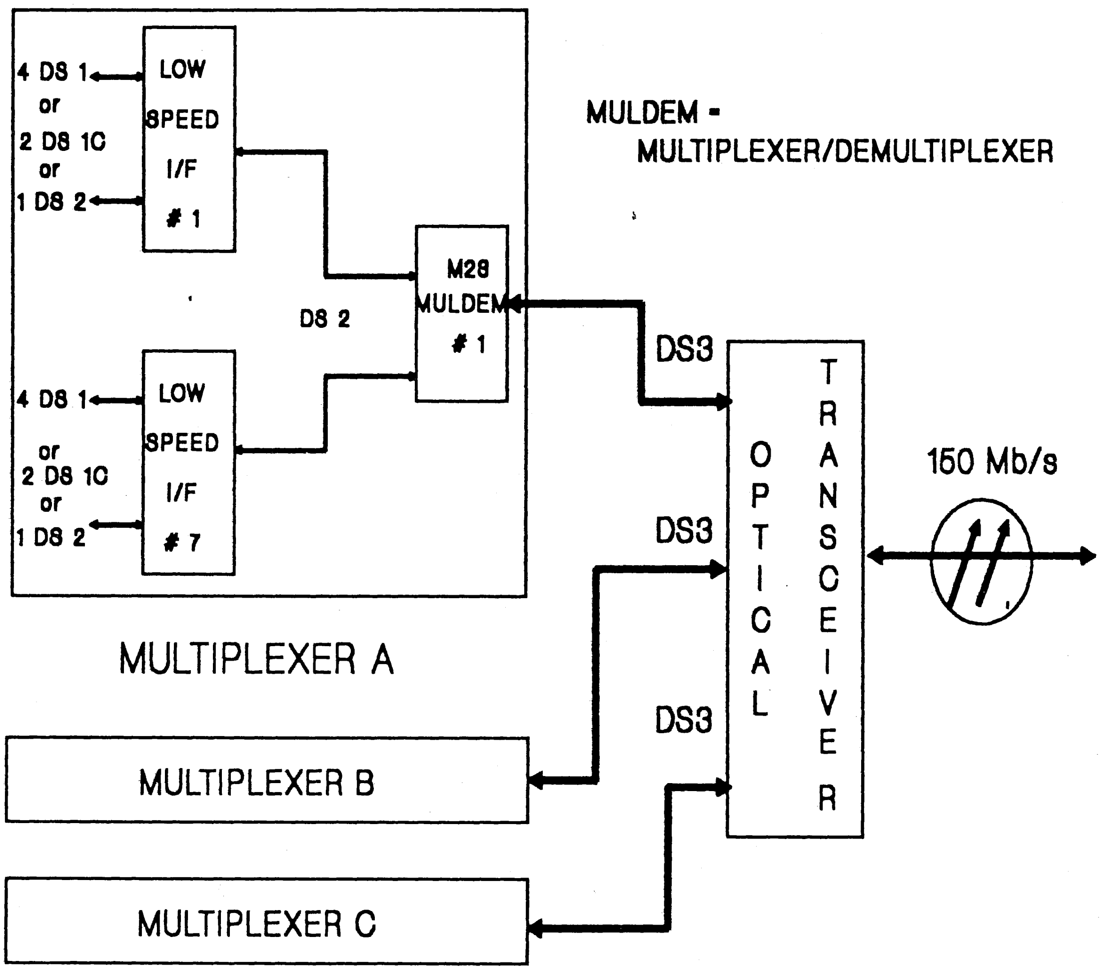
FIGURE 2-1
45 MB/S DIGITAL MULTIPLEXER
WITH LIGHTWAVE TRANSMISSION CAPABILITY



NOTE: For clarity, this figure does not show redundancy.

2.2.3 The block diagram in Figure 2-2 illustrates a lightwave transmission system with an integral multiplexer. This figure illustrates a 150 Mb/s system. In effect, the 45 Mb/s lightwave transmission system with an integral multiplexer would look the same as the digital multiplexer with lightwave transmission capability shown in Figure 2-1.

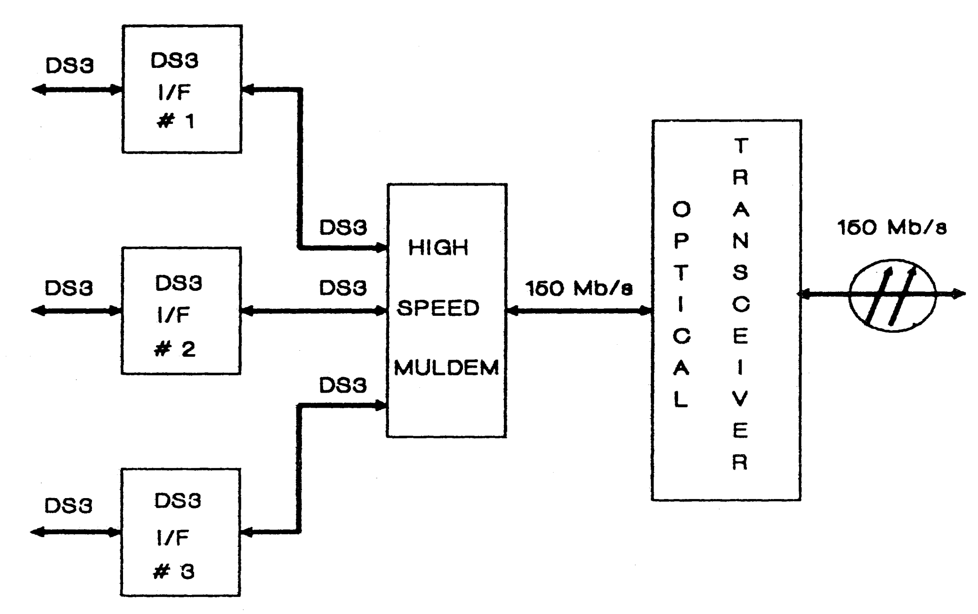
FIGURE 2-2
150 MB/S LIGHTWAVE TRANSMISSION SYSTEM
WITH INTEGRAL MULTIPLEXER



NOTE: For clarity, this figure does not show redundancy.

2.2.4 Figure 2-3 provides a block diagram of a lightwave transport system. In a system of this type the electrical input is at the DS3 level. In general, from 1 to 12 DS3s can be interfaced depending on the bit rate of the system. (Systems exist that can interface many more than 12 DS3s and provide bit rates much higher than 565 Mb/s but rural applications have generally not required these systems.)

FIGURE 2-3
150 MB/S LIGHTWAVE TRANSPORT SYSTEM



NOTE: For clarity, this figure does not show redundancy.

2.2.5 Table 2-1 shows the standard bit rates and the equivalent voice channels for the North American digital hierarchy. This table will be useful in the understanding of the following paragraphs.

TABLE 2-1
STANDARD NORTH AMERICAN DIGITAL HIERARCHY

Digital Signal Level	Number of Equivalent Voice Circuits	Transmission Rate (Mb/s)
DS1	24	1.544
DS1C	48	3.152
DS2	96	6.312
DS3	672	44.736
DS4	4032	274.176

2.2.6 Most of today's lightwave systems that include integral multiplexers use MX3-type multiplexers. This is the type shown in Figures 2-1 and 2-2. Generally, the low speed electrical input consists of a maximum of seven (7) interface cards per DS3 output. Figure 2-1 shows 7 input cards for a 45 Mb/s system (1 DS3) and Figure 2-2 shows 21 cards for a 150 Mb/s system (3 DS3s). Practically, the terminal needs only the number of cards required to interface the actual number of inputs.

2.2.6.1 Each of the low speed interface cards can terminate a variety of inputs as shown in Figure 2-1, i.e., 4 DS1s, 2 DS1Cs or 1 DS2. Therefore, 7 cards enable the system to interface a total of 28 DS1s, 14 DS1Cs or 7 DS2s. Additionally, any combination of inputs equivalent to 28 DS1s can be interfaced. For example, 20 DS1 (5 cards), 2 DS1C (1 card), and 1 DS2 (1 card) inputs could be equipped.

2.2.7 For clarity, Figures 2-1, 2-2 and 2-3 illustrate the systems without redundancy. Paragraph 2.5 describes various protection schemes in some detail.

2.3 Lightwave Sources

2.3.1 By definition, the source of a lightwave terminal is a source of light energy. The two types of sources used in today's lightwave terminals are the light emitting diode (LED) and the injection laser diode (ILD) or simply laser.

2.3.2 When determining the type of source to utilize, several characteristics must be carefully considered.

2.3.2.1 The switching speed of the source (how fast it can turn off and on) determines the maximum optical bit rate at which the terminal is able to operate.

2.3.2.2 The output power level determines the distance that an optical signal can be transmitted without the necessity for regeneration.

2.3.2.3 The wavelength of the light emitted by the source must be able to be passed through the connected optical fiber at a low loss.

2.3.2.4 The spectral width of the source must be small enough so as to minimize dispersion in the optical fiber.

2.3.3 Light Emitting Diode - The emission of photons when a current passes through a gallium arsenide p-n junction is the basis for the operation of a light emitting diode (LED). A variety of dopants such as indium, aluminum and phosphorus produce different wavelengths of light.

2.3.3.1 Generally speaking, LEDs produce less output power than lasers. However, the output power of an LED is relatively independent of temperature. Thus, these devices are simple and correspondingly inexpensive and have a long operating life.

2.3.3.2 Since LEDs have a large spectral width and low output power, they are not suitable for high bit rate systems or long link lengths.

2.3.4 Laser - Laser is the accepted acronym for Light Amplification by Stimulated Emission of Radiation. A laser generates a single wavelength, or a narrow band of wavelengths, of light. More importantly, the light produced by a laser is continuously coherent, i.e., in phase. This coherence allows large power outputs.

2.3.4.1 A laser operates like an LED until the drive current reaches a threshold level. At that point, photons created by current passing through the p-n diode junction cause additional photons to be emitted. This process is lasing.

2.3.4.2 Figure 2-4 shows that for a small increase in drive current above the threshold, a large increase in output power occurs. As the laser emits more and more photons, its temperature increases. With this increase, the threshold current also increases and the corresponding output power changes. Figure 2-5 shows the temperature dependency of the output power. The output wavelength is also temperature dependent.

2.3.4.3 The temperature dependency characteristics of a laser makes it necessary to provide circuitry to control the laser temperature which makes the device more complex and correspondingly more expensive.

2.3.4.4 In that lasers produce high output power and have a narrow spectral width, they can be used in high bit rate systems and for transmission over long link lengths.

FIGURE 2-4
SOURCE OUTPUT POWER VS DRIVE CURRENT

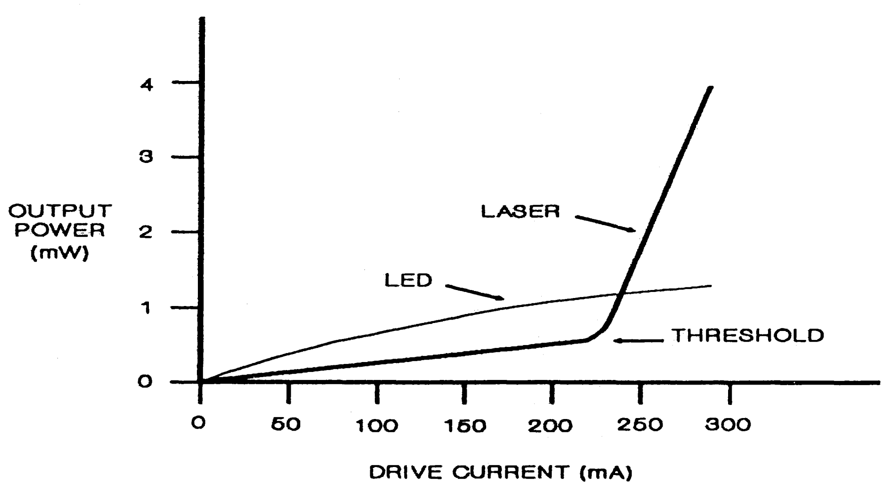
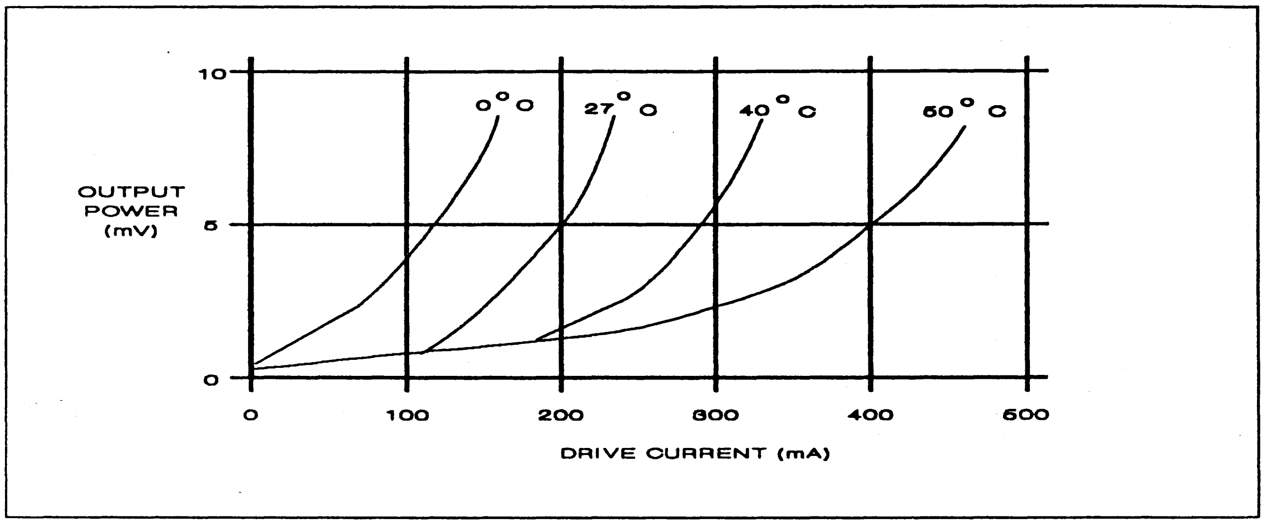


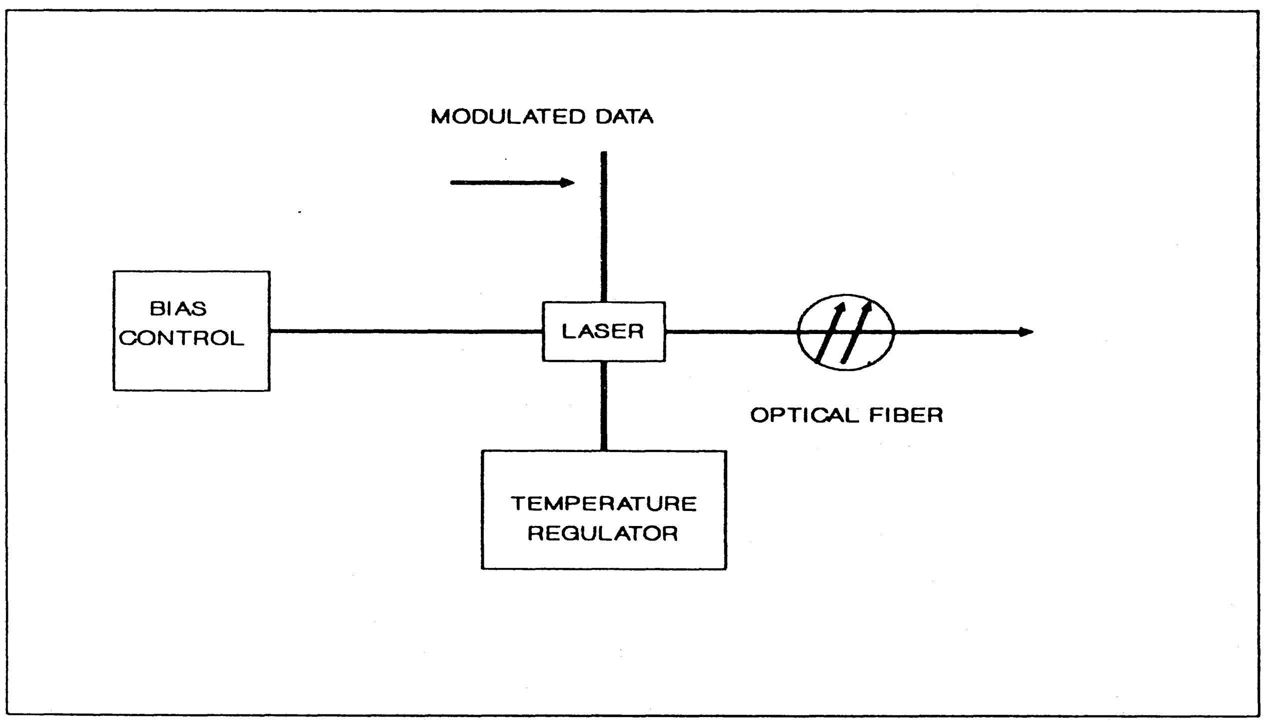
FIGURE 2-5
TEMPERATURE DEPENDENCE OF LASER OUTPUT



2.3.5 Figure 2-6 is a block diagram of a typical laser transmitter. The laser converts the incoming modulated electrical data into an optical signal that the lightwave terminal then couples to an optical fiber.

2.3.5.1 In addition to the laser diode itself, the transmitter contains certain adjunct components to ensure proper operation.

FIGURE 2-6
LASER TRANSMITTER



2.3.5.1.1 The bias control ensures a constant average optical output.

2.3.5.1.2 The temperature regulator keeps the laser temperature constant (about 20°C).

2.3.5.2 Normally the transmitter launches the output of the laser into a fiber pigtail attached to the transmitter. This pigtail enables convenient connection to the transmission fiber.

2.3.6 A large percentage of the lightwave transmission systems available today operate at a wavelength of 1310 nanometers. Table 2-2 shows typical minimum, maximum and average operating levels for sources at this wavelength.

TABLE 2-2
TYPICAL OPERATING LEVELS FOR
OPTICAL SOURCES AT 1310 NM

	Output (dBm)		
Type	Minimum	Maximum	Average
ILD	-17	+1.5	-5
LED	-33	-14.0	-24

2.4 Lightwave Detectors

2.4.1 An optical detector converts incoming light energy into an equivalent electrical bit stream. Today's lightwave system terminals use positive-intrinsic-negative (PIN) photodiodes or avalanche photodiodes (APD) as detectors.

2.4.2 Various characteristics of these detectors must be considered in making a selection of the type of detector to employ.

2.4.2.1 The detector's responsivity provides the relationship between its input voltage or current and its output power.

2.4.2.2 The response time is the time required for the output to rise from 10% to 90% of the detector's peak output power.

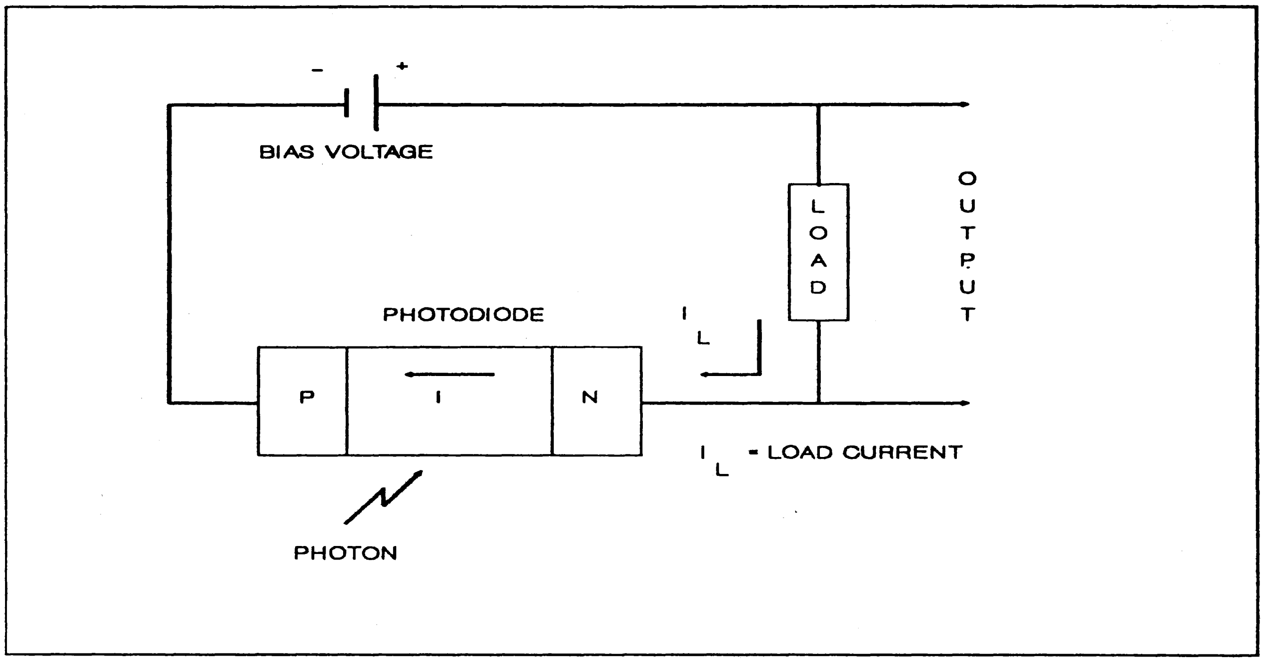
2.4.2.3 Dark current, which is analogous to leakage current in pure electrical circuits, is the current that flows in the receiver circuitry in the absence of an incoming lightwave signal.

2.4.2.4 The quantum gain of a detector is the ratio of incoming photons to outgoing electrons. A gain of 1, or 100%, means that every incident photon causes an electron to flow in the external receiver circuit.

2.4.3 A PIN photodiode is a semiconductor chip composed of a P-doped region and an N-doped region separated by an intrinsic region (pure semiconductor without P or N doping).

2.4.3.1 When light energy strikes the photodiode, current flows in the photodiode and in the external circuitry as shown in Figure 2-7. The gain of a PIN photodiode is typically less than 1. That is, every incident photon does not produce an electron in the receiver circuit.

FIGURE 2-7
PHOTODIODE CIRCUITRY



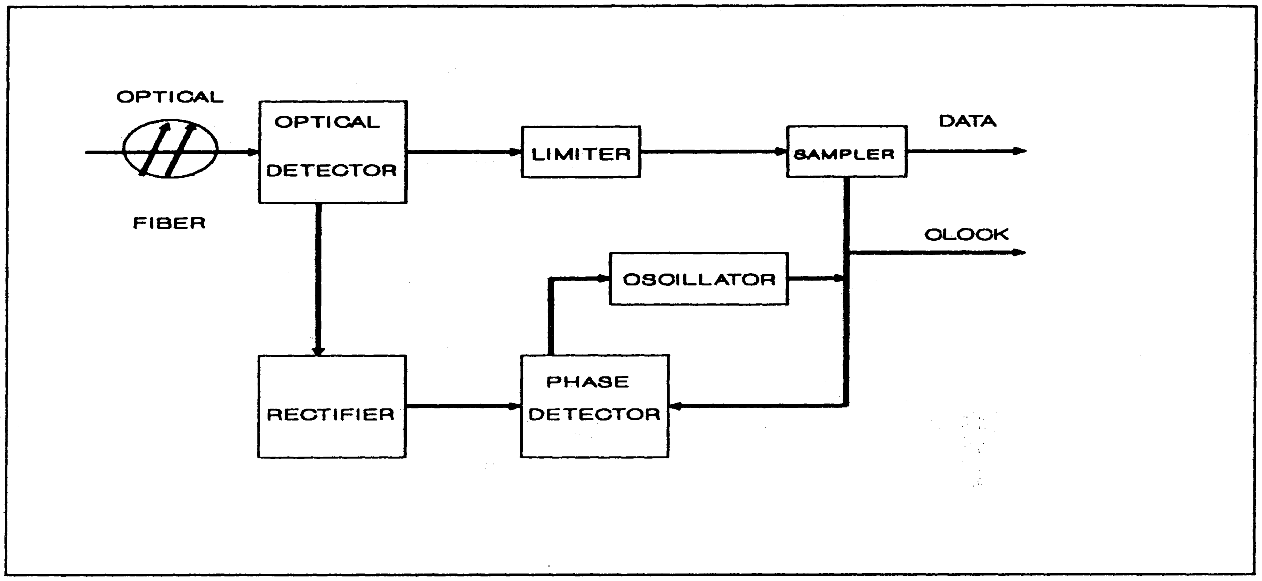
2.4.4 To increase the output and the responsivity of the detector, an avalanche photodiode (APD) can be used. In the APD, the semiconductor material itself amplifies the current flow caused by the incident light. The gain of an APD is greater than 1. In other words, each incident photon usually causes more than one electron to flow in the receiver circuit.

2.4.5 APDs require a high bias voltage and are more expensive than PIN photodiodes. In addition to the higher output, an APD has a faster response time than a PIN photodiode.

2.4.6 Figure 2-8 shows a block diagram of a typical optical receiver. This receiver converts an incoming lightwave data stream into an equivalent electrical bit stream.

2.4.6.1 The optical detector consists of a PIN photodiode or an APD. The output of the detector is an electrical equivalent of the incoming optical signal. The remainder of Figure 2-8 contains basic circuitry to recover the clock timing. The phase detector and the oscillator form a phase locked loop that recovers the clock. As is the case for the optical transmitter described earlier, an integral fiber pigtail connects the transmission fiber to the receiver.

FIGURE 2-8
OPTICAL RECEIVER



2.4.7 Table 2-3 shows typical minimum, maximum and average operating levels for detectors at 1310 nanometers, the most common wavelength used in today's systems.

TABLE 2-3
TYPICAL OPERATING LEVELS FOR
OPTICAL DETECTORS AT 1310 NM

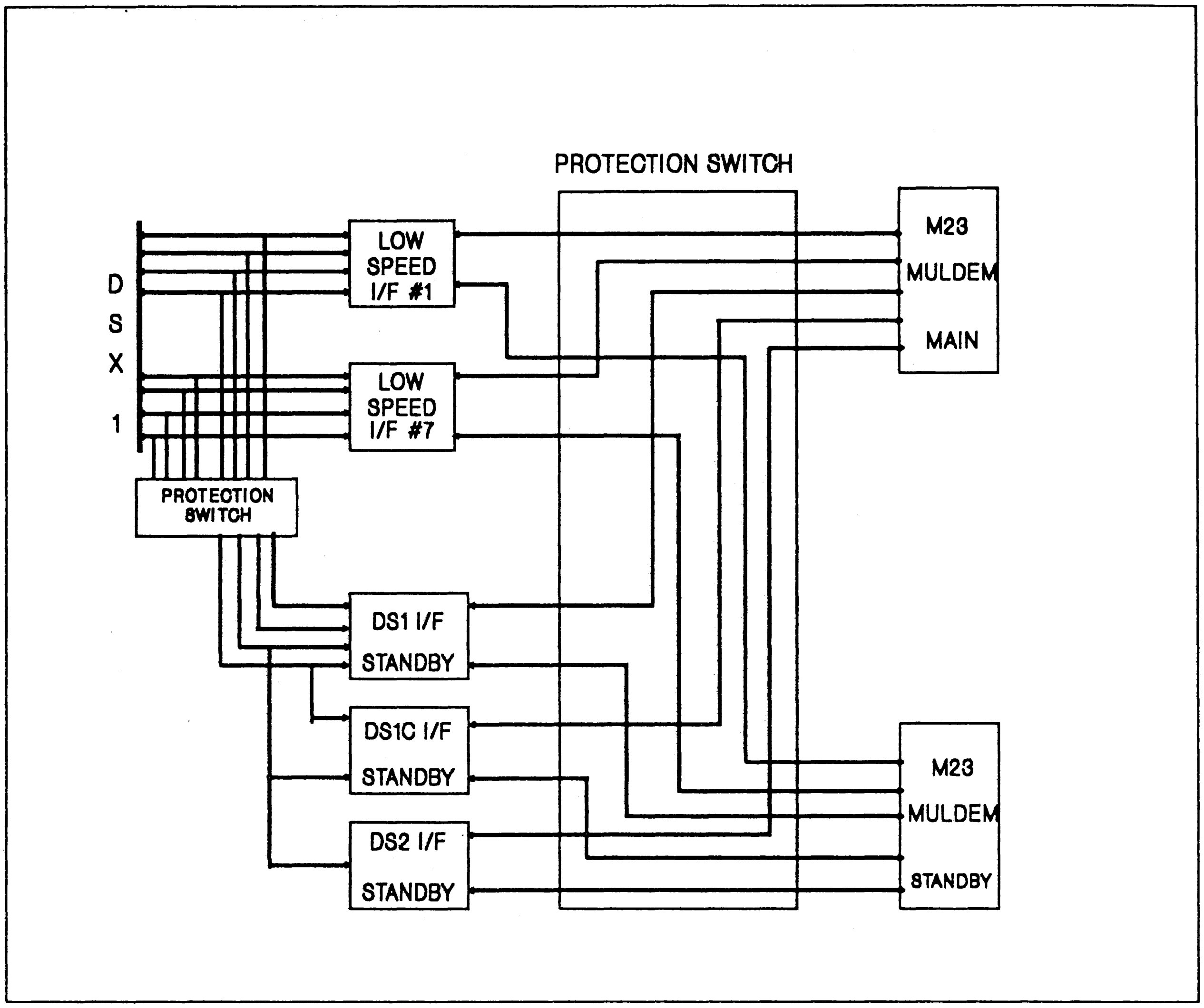
Type	Sensitivity (dBm) Minimum	Maximum	Average
APD	-61	-30	-42
PIN	-50	-22	-39

2.5 Service Protection

2.5.1 Typically, lightwave systems with integral MX3-type multiplexers provide low speed protection in the ratio of 1:N where N is equal to the number of low speed interface cards equipped up to a maximum of seven (7). (Some systems are also available with 1:1 low speed protection.)

2.5.2 Figure 2-9 shows a typical low speed protection scheme. This figure shows one protection interface card for each input level, i.e., DS1, DS1C, and DS2. For most of today's systems, only one protection card can be operational at any given time. For example, if a standby DS1 card is operational, the system can not protect a subsequent DS1C failure. Obviously, it is necessary to provide standby cards only for equipped input levels. Figure 2-9 also illustrates the M23 muldem protection scheme.

FIGURE 2-9
LOW SPEED INTERFACE PROTECTION

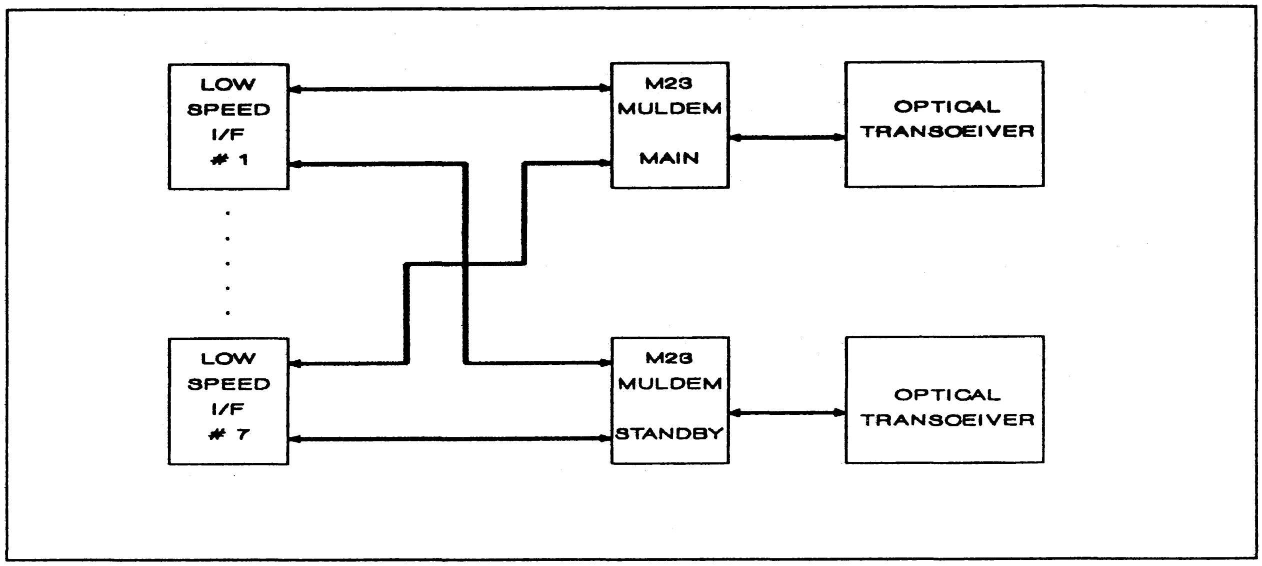


2.5.2.1 Certain lightwave transmission systems provide priority protection for the low speed interfaces. In this arrangement, certain low speed interface cards can be assigned higher protection priority than others. If the terminal is protecting a lower priority card when a card of higher priority fails, the system switches in the standby interface card to protect the higher priority card.

2.5.2.2 Some lightwave transmission systems protect the transmit and receive circuits independently.

2.5.3 Systems without low level multiplexers, i.e., where the low level input is at the DS3 level, normally provide 1:1 protection. This is also the case for the high speed portion of the systems. Figure 2-10 illustrates 1:1 high speed protection. Some systems have the optical transceiver and the M23 muldem mounted on the same printed circuit card. In other systems they are on separate cards. In the latter case, the optical transceiver is usually separately protected on a 1:1 basis as well. It is also possible to configure most lightwave systems as unprotected systems if desired.

FIGURE 2-10
HIGH SPEED PROTECTION

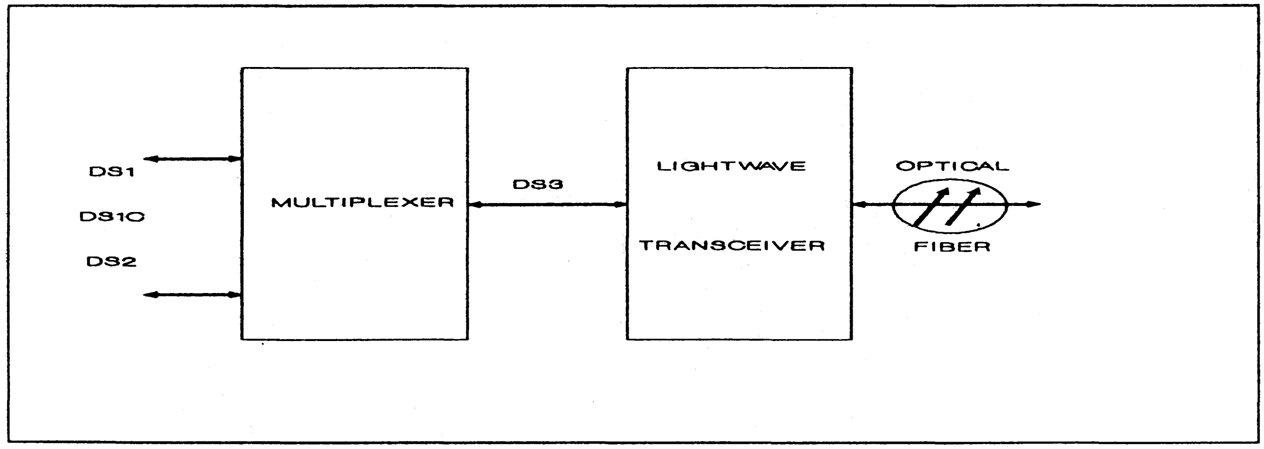


2.6 Lightwave System Configurations

2.6.1 Four basic arrangements are generally available for lightwave transmission systems.

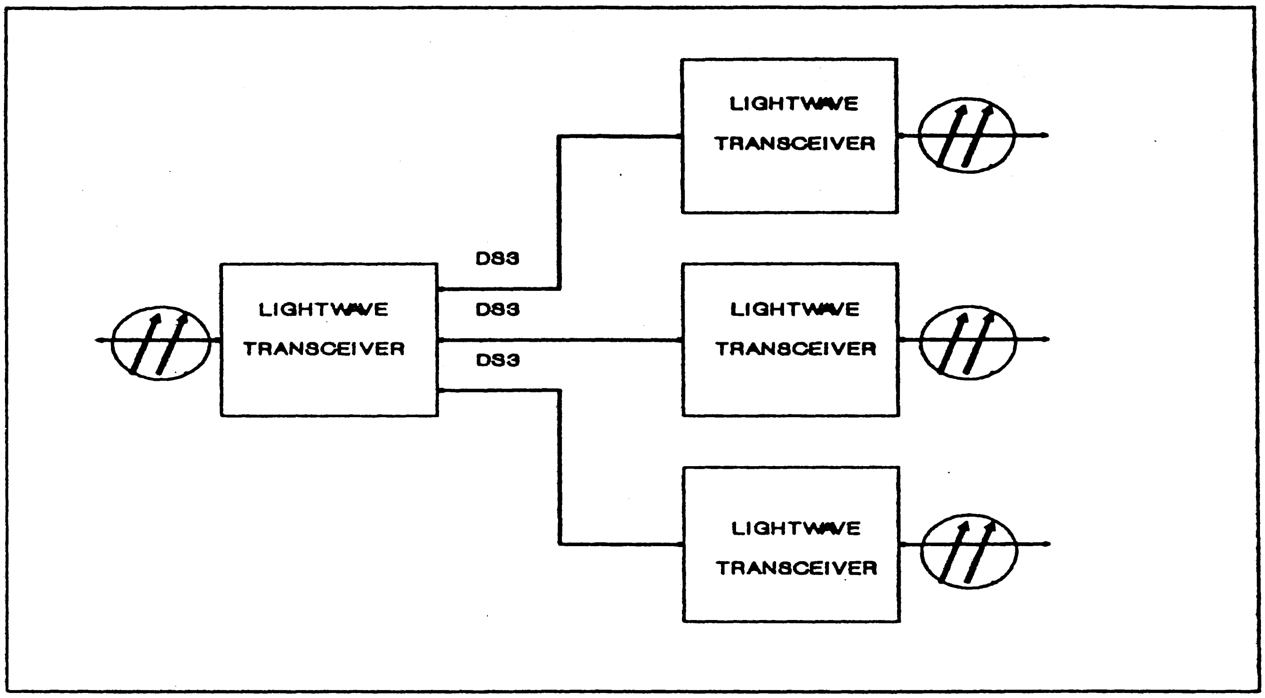
2.6.1.1 The terminal configuration as shown in Figure 2-11 converts an optical signal into electrical bit streams at a terminal location, e.g., a central office.

FIGURE 2-11
TERMINAL SITE CONFIGURATION



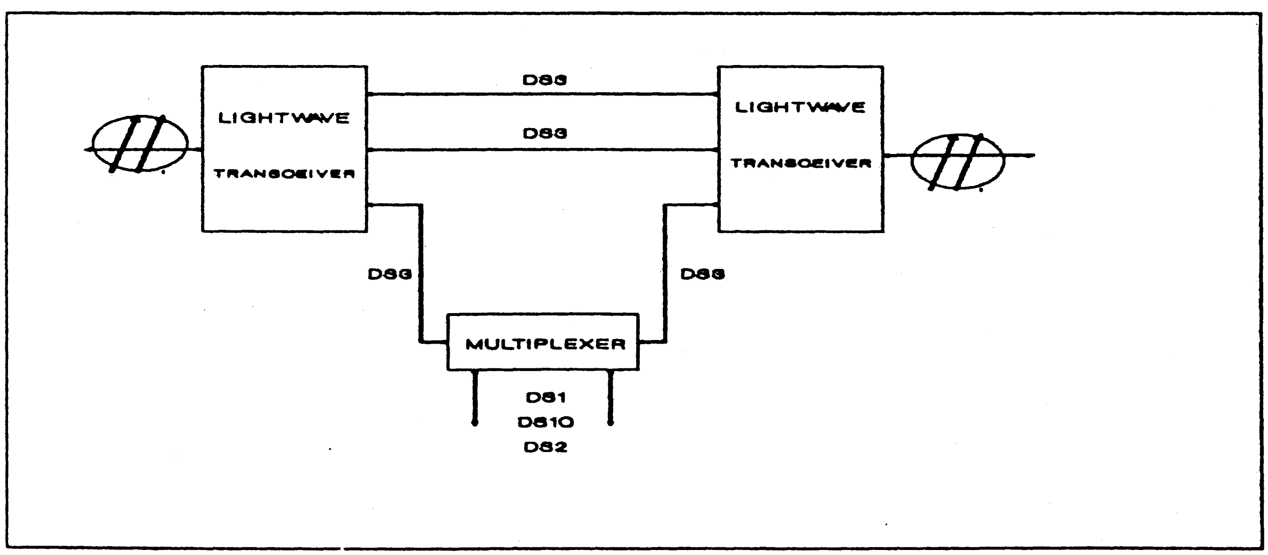
2.6.1.2 Figure 2-12 shows a hub configuration. This configuration enables a single high rate optical signal to be split into several lower rate optical signals and vice versa.

FIGURE 2-12
HUB SITE CONFIGURATION



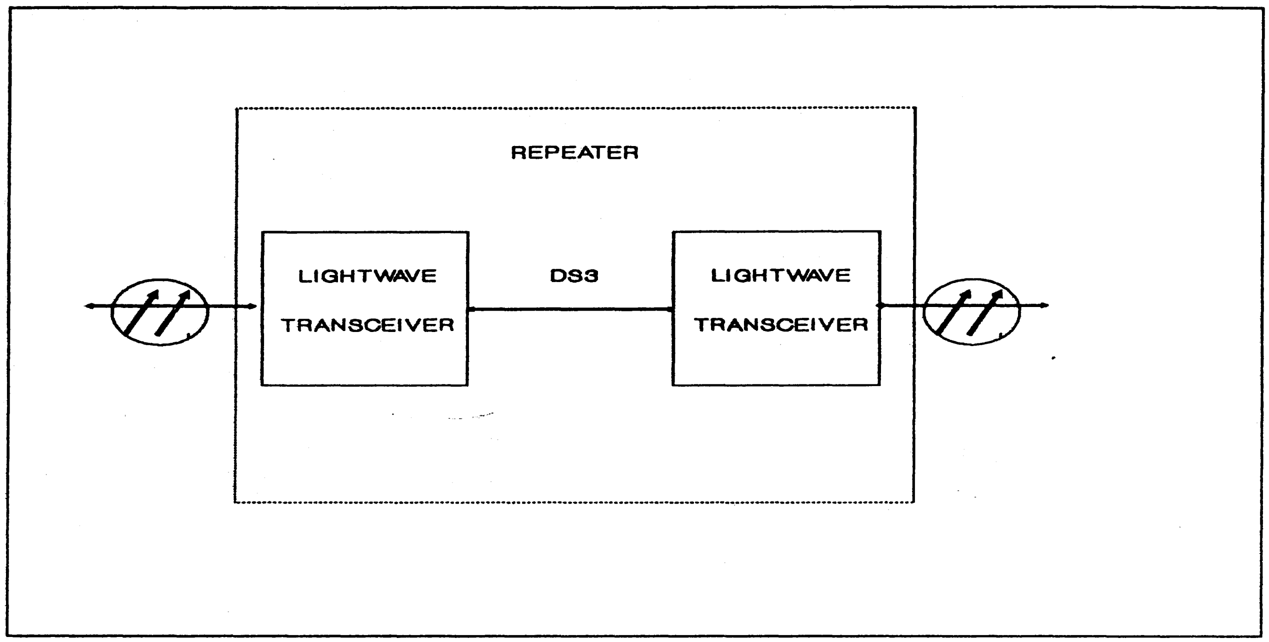
2.6.1.3 As illustrated in Figure 2-13, the drop/insert configuration enables a portion of an incoming optical signal to be demultiplexed into lower level electrical bit streams at an intermediate (tandem) location. At the same point, lower level signals can be inserted into the optical signal.

FIGURE 2-13
DROP/INSERT SITE CONFIGURATION



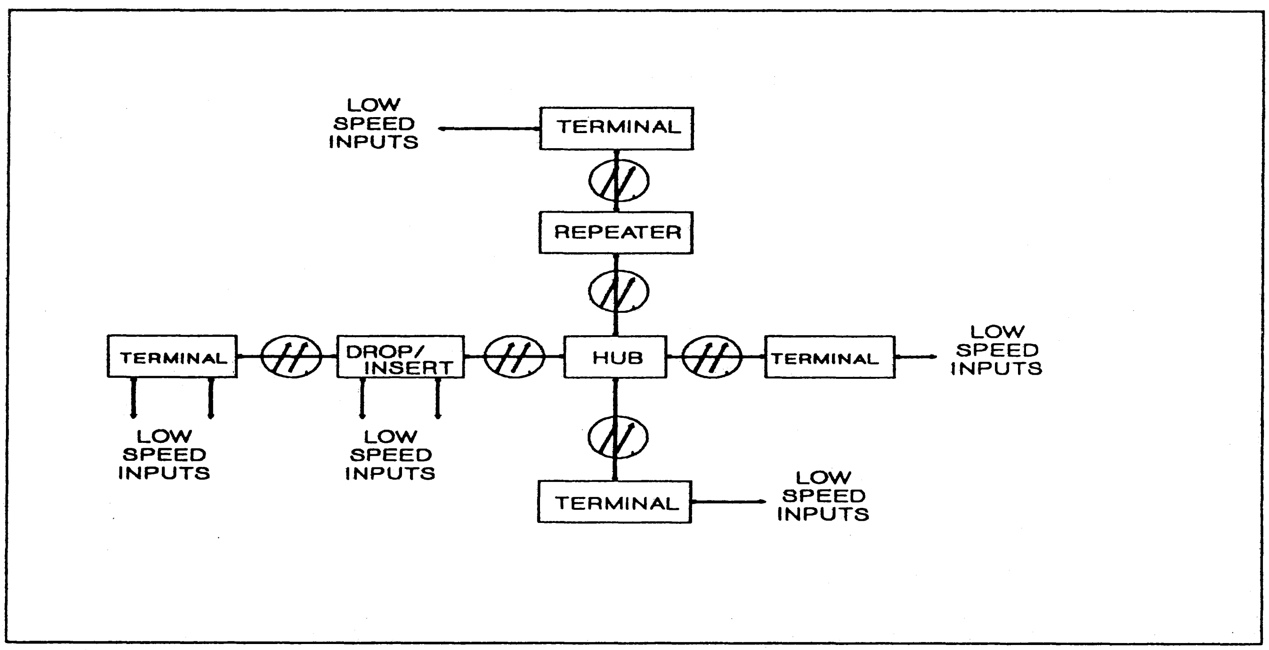
2.6.1.4 The optical repeater shown in Figure 2-14 provides regeneration for weakened optical signals in long lightwave links.

FIGURE 2-14
LIGHTWAVE REPEATER SITE



2.6.1.5 Figure 2-15 illustrates a network configuration using each of the four possible site arrangements.

FIGURE 2-15
NETWORK CONFIGURATION

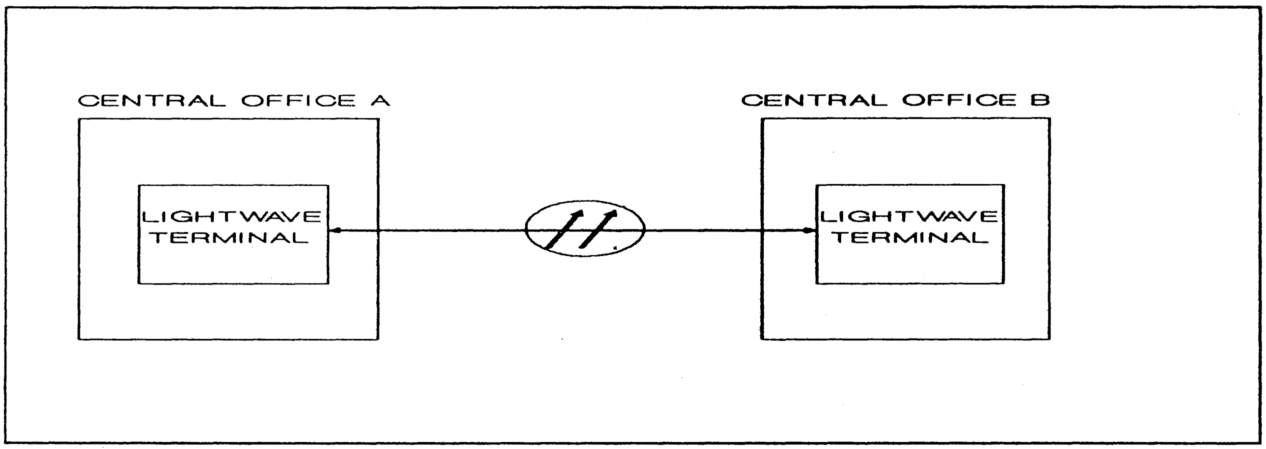


2.7 <u>Typical Applications</u>

2.7.1 Lightwave transmission systems can be utilized in many varied applications.

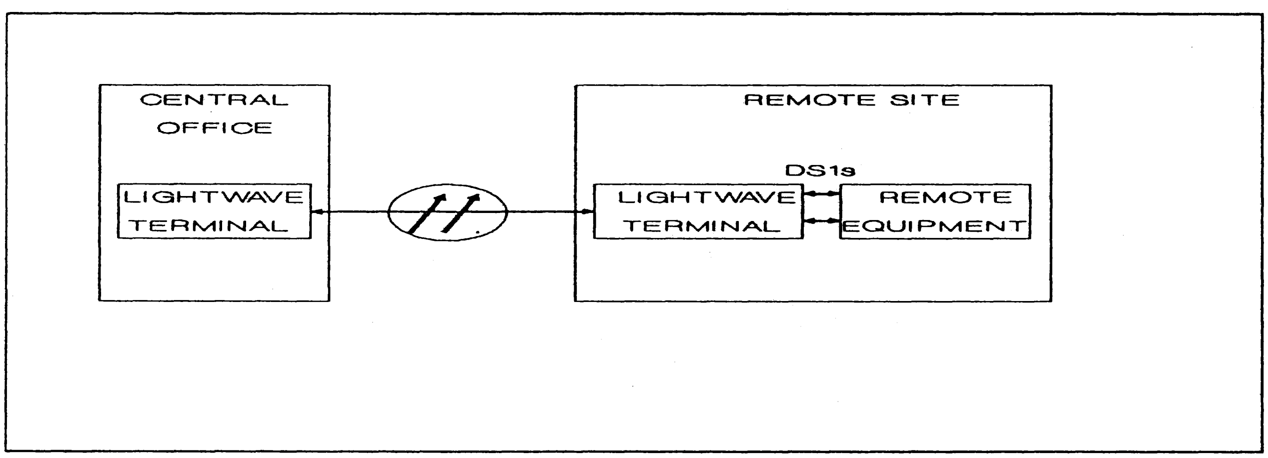
2.7.1.1 Historically, the most common application has been interoffice trunking. Figure 2-16 illustrates this application.

FIGURE 2-16
INTEROFFICE TRUNK ROUTE



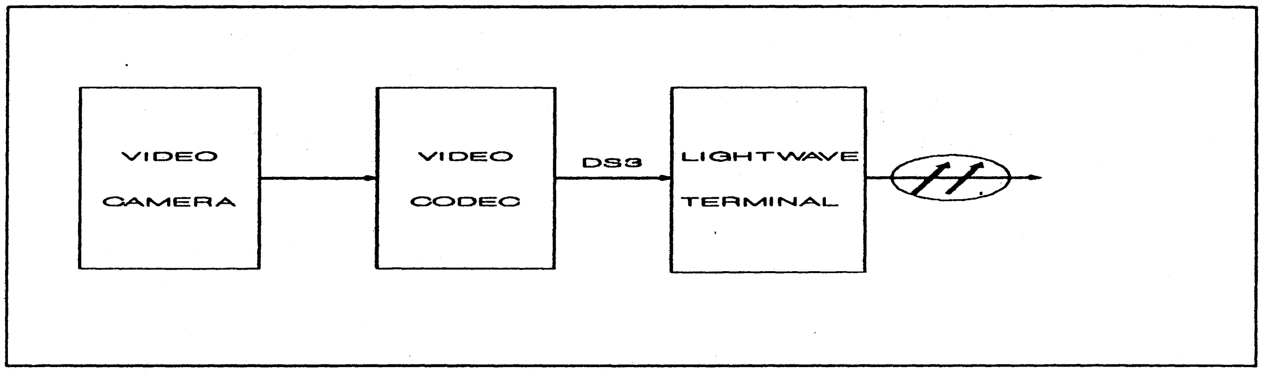
2.7.1.2 In recent years lightwave equipment has connected central offices to remote sites (feeder routes). These sites consisted of digital loop carrier, remote switching terminals (RST) and customer premises equipment. Figure 2-17 shows this arrangement.

FIGURE 2-17
CENTRAL OFFICE TO REMOTE SITE



2.7.1.3 Figure 2-18 illustrates one of the more recent applications of lightwave transmission equipment. In this application, the lightwave terminal transports video signals.

FIGURE 2-18
BROADBAND APPLICATION



2.7.2 Wavelength Division Multiplexing (WDM) enables more than one optical signal to be transmitted over the same fiber. Each signal uses a different wavelength of light for transmission.

2.7.3 With this technology it is possible to use a single fiber for bidirectional transmission as shown in Figure 2-19. Figure 2-20 illustrates how WDM can be used to transmit separate signals in the same direction over a single fiber.

FIGURE 2-19
WAVELENGTH DIVISION MULTIPLEX - BIDIRECTIONAL

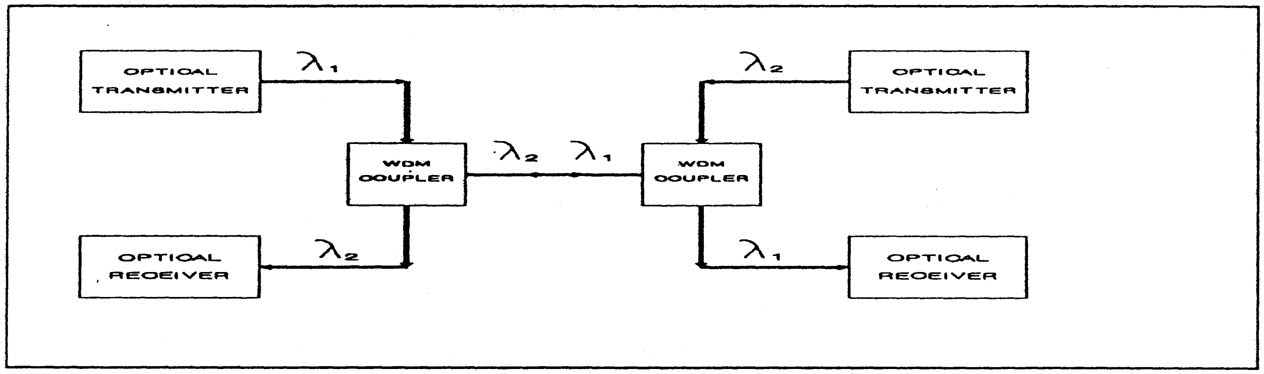
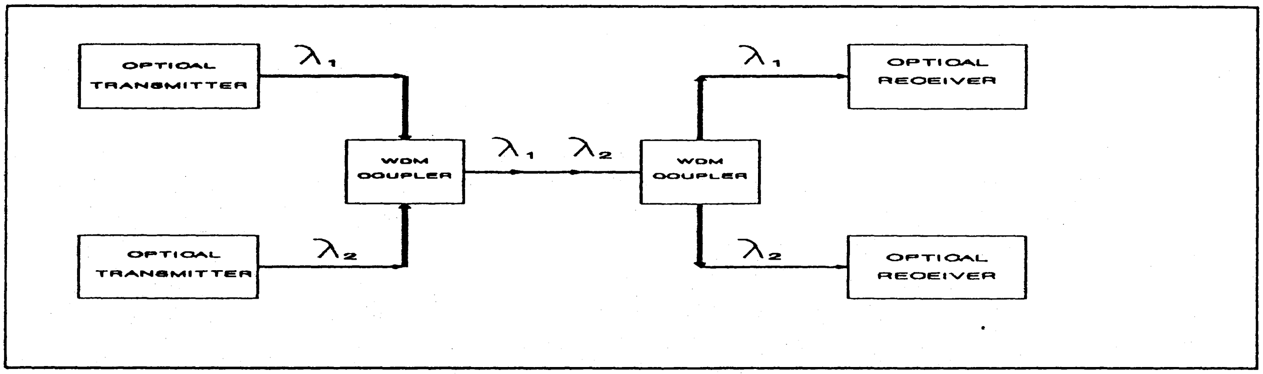


FIGURE 2-20
WAVELENGTH DIVISION MULTIPLEX - ONE-WAY



2.7.4 WDM can be used for the following specific purposes.

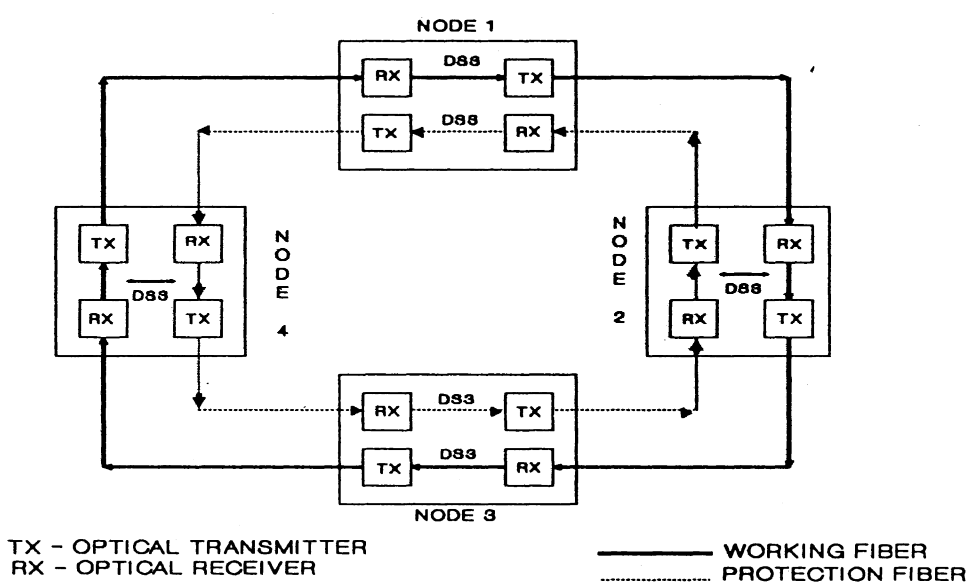
2.7.4.1 Recovery of Fiber - Since WDM allows a single fiber to be used for two-way transmission, a second fiber can provide a new optical link installation rather than a facility for a second transmission direction.

2.7.4.2 Optical Drop and Insert - WDM couplers can be used to drop/insert optical signals transmitted at one wavelength while passing other wavelengths of light directly through the site.

2.7.4.3 Capacity Increase - When the fiber capacity reaches its limit, WDM can be used to increase the capacity of the existing fiber.

2.7.5 Figure 2-21 illustrates one type of ring configuration that can be used to protect against service failures, particularly cable cuts. This figure shows a four node network interconnected by a fiber cable. Under normal conditions such as shown in Figure 2-21, the fiber identified as the working fiber carries the traffic. The protection fiber does not carry any traffic under normal circumstances.

FIGURE 2-21
RING CONFIGURATION - NORMAL OPERATION

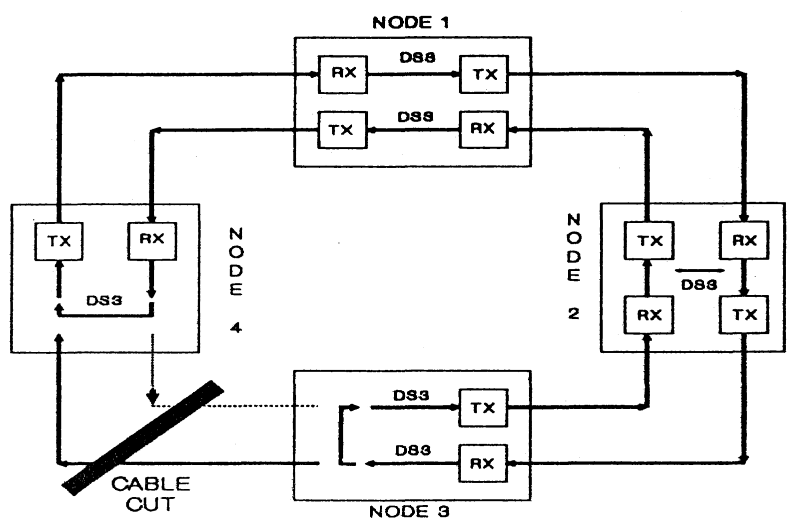


2.7.6 Figure 2-22 shows the protection configuration in the event of a cable cut. In this configuration both the working fiber and the protection fiber carry traffic. Switching circuitry in the terminal equipment provides the proper path (Nodes 1 and 2 in Figure 2-22).

2.7.6.1 Since the fiber cable cut occurred between nodes 3 and 4, direct communications between these nodes is not possible via the working fiber. In essence, the system reconfigures the network to permit communication between nodes 3 and 4 over the protection fiber as shown in Figure 2-22.

2.7.6.2 Electrical switches in nodes 1 and 2 operate to reconfigure the terminal equipment as regenerators.

FIGURE 2-22
RING CONFIGURATION - PROTECTED OPERATION



2.8 Maintenance Features

2.8.1 Various types of maintenance features are available with lightwave transmission systems. However, not all systems provide all the features described in the following paragraphs.

2.8.2 The following types of peripheral interfaces are available.

2.8.2.1 One or more RS-232 interfaces are available to enable connection of various control and display equipment such as local CRT terminals or maintenance units designed to work with specific systems. This interface type also connects dial-up modems.

2.8.2.2 One or more serial interfaces can be provided to allow connection of compatible telemetry alarm systems. Such systems provide remote alarm and status indications and enable remote control functions to be used.

2.8.2.3 Relay interfaces provide dry contact closures to provide connections for remote alarm and status points.

2.8.3 Various types of auxiliary channels can be provided. The lightwave terminal integrates (multiplexes) these channels into the overhead of the optical data stream.

2.8.3.1 Two order-wire channels, express and local, are available to provide two-way voice communications between lightwave equipment sites, e.g., terminals and repeaters. The express order-wire channel is accessible only at terminal locations whereas the local order-wire channel can be used at all sites.

2.8.3.2 One or more inband data channels, typically 64 kb/s, may be provided for customer usage, e.g., to carry digital alarm and control data and order-wire data between sites.

2.8.3.3 One or more DS-1 channels may be available for customer usage to transmit digital data between lightwave sites. Like the order wire channels, these may be express or local.

3. LIGHTWAVE SYSTEM APPLICATION GUIDELINES

3.1 General

3.1.1 This section provides REA borrowers and other interested parties with general guidelines regarding the application and design of lightwave transmission systems. In general, this section pertains to interoffice trunks and links to Remote Switching Terminals(RST), subscriber carrier terminals, and concentrators. This section does not discuss lightwave equipment providing loop service, i.e., the "Last Mile" or "Fiber to the Home." In addition, this section does not consider synchronous optical transmission systems, e.g., SYNTRAN and SONET but Section 5 discusses these systems. Guidelines given in this section should be considered as such and varied as a particular situation warrants.

3.2 Application Engineering

3.2.1 The nature of optical fiber and the availability of various types of lightwave terminals provide many options for designing any particular lightwave system. Even though a single optical fiber can provide a large transmission bandwidth, it is necessary to design a system that not only provides the required traffic capacity but also ensures sufficient reliability and economic feasibility. Application engineering generally develops system configurations that not only satisfy the technical performance requirements but also provide sufficient capacity for both initial and future traffic requirements.

3.2.2 It is important to consider the many factors involved in the system during the initial design phase of a lightwave link. Lacking careful consideration during this stage, the design may provide a large excess capacity that the system may never require and therefore, a substantial economic penalty would be paid. In addition, technological obsolescence can be particularly costly when lightwave systems with large unused capacity must be replaced. The advent of new technical standards such as SONET enhances the importance of prudent system design in that such changes can produce rapid obsolescence of terminal equipment. On the other hand, if the design does not provide for sufficient capacity initially and is inflexible, a large equipment change out may be required when the system requires additional capacity. This also would be a costly situation.

3.2.3 The fact that fiber optic facilities are quite different in nature from paired copper cables should influence lightwave application engineering. A single optical fiber can provide a large amount of transmission bandwidth capability. Traffic capacity of paired cable plant is generally directly proportional to the pair count. That is, when traffic requirements exceed the pair count capacity, additional pairs must be provided. The use of pair gain equipment such as carrier systems alters this situation to a certain extent, however, the ultimate factor in determining the facility's traffic carrying capacity remains the pair count.

3.2.4 The electro-optical terminal devices and the characteristics of the optical fiber determine the transmission capacity of a lightwave link. If the inherent characteristics of the fiber provide the required bandwidth, the terminal devices or terminal configurations alone are the determinant factors of the traffic capacity. It is important for the lightwave system designer to understand that the fiber count versus traffic capacity relationship has little relevancy in lightwave system design, especially for conventional telecommunication applications and particularly in rural applications where the traffic is light. This may not necessarily be the case for wideband applications such as television.

3.2.5 Although a single fiber may have sufficient bandwidth to satisfy the traffic requirements, possibly even enough for bidirectional transmission, there are normally compelling reasons to provide additional fibers in the link. This section discusses these reasons later.

3.3 Multiplexing

3.3.1 The most common technique in use today for increasing transmission capacity is higher level digital multiplexing. This technique combines several lower bit rate digital signals into a single higher bit rate pulse stream. Digital multiplexing results in a higher transmission rate that requires a wider bandwidth. This increased bandwidth requirement may result in higher fiber performance requirements or more sophisticated lightwave terminal equipment specifications and therefore, increased system costs. In addition, digital multiplexing introduces a higher degree of terminal equipment commonality that may require redundant, automatically switched units to protect against total outages.

3.3.2 Many of today's lightwave transmission systems use an MX3 type multiplexer. Multiplexers of this type are available as stand-alone units or as integral parts of lightwave transmission systems. Additionally, some of these stand-alone multiplexers can be converted to lightwave systems by replacing the electrical card(s) with one or more cards containing optical transmitter and receiver components. An MX3 multiplexer is capable of combining up to 28 DS1, 14 DS1C, or 7 DS2 inputs into a single DS3 output. It is also possible to combine different input rates up to an equivalent maximum of 28 DS1s, e.g., 14 DS1s, 5 DS1Cs, and 1 DS2. Typically, the multiplexer input consists of up to seven low speed interface cards each of which can provide interface for 4 DS1, 2 DS1C, or 1 DS2 bit streams. Because of the modular nature of these systems, they can be equipped to handle the initial traffic only and as traffic growth warrants, additional hardware can be added. For example, a lightwave terminal requires only three low speed interface cards when the initial traffic requirement is 10 DS1s.

3.3.3 Lightwave transmission systems are available that can multiplex DS3 inputs to provide optical outputs equivalent to 2, 3, or 4 DS3s. Higher density systems, e.g., 565 Mb/s are also available.

3.3.4 Another method of increasing the capacity of a lightwave link is the use of Wavelength Division Multiplexing (WDM). This technique allows more than one lightwave signal to be transmitted simultaneously via a single fiber by using different wavelengths for each signal. WDM also can enable bidirectional transmission. The WDM technique is analogous to Frequency Division Multiplexing used in cable carrier systems.

3.3.5 Filters, commonly called WDM couplers, can separate and combine the various wavelengths at the ends of the link. The lightwave terminals must have separate transmitters and receivers for each wavelength used.

3.3.6 Long haul toll applications have used the WDM technique. Loop applications also may use WDM extensively in the future. Although WDM is technically practicable and bears consideration in certain situations, rural applications have not made widespread used of the technology. The WDM equipment, although a small portion of the total system investment, may be a key factor in the overall system practicability. Since suppliers other than those who provide the terminal equipment or the fiber optic cable generally furnish the WDM couplers, this technique introduces another player to divide the area of responsibility should problems arise.

3.3.7 Another device finding limited usage is the Optical Directional Coupler (ODC). The ODC separates or combines lightwave signals of the same wavelength. These devices, although less expensive than WDM couplers, generally introduce more loss. ODCs can be utilized to provide bidirectional lightwave transmission without requiring a transmitter and a receiver that operate at a different wavelength for the second signal.

3.3.8 Interoffice trunk applications and links to RSTs, carrier systems and concentrators generally require lightwave systems with a minimum data rate of 45 Mb/s. There appears to be little cost advantage on lower rate systems since the 45 Mb/s rate is nearly as easy to obtain as the 6 Mb/s rate because of the nature of transmitters, receivers, and optical fibers.

3.4 Redundancy

3.4.1 As mentioned previously, the higher degree of commonality associated with digital multiplexing requires redundancy to protect against total outages. Today's lightwave systems provide this protection in several ways. Normally, when a multiplexer is an integral part of the lightwave system, it is an MX3 type with low speed interfaces protected by a standby interface card for each of the installed input levels, i.e., DS1, DS1C, or DS2. Since the multiplexer can be configured for up to seven interface cards, low speed protection is 1:N, where N is 1 to 7 depending on the number of interface cards installed. The system normally protects the high speed electrical and optical portions on a 1:1 basis, i.e., the high speed multiplex, transmitter, and receiver equipments are completely redundant. Generally, this redundancy is optional. It is a management decision to determine whether the benefits of the redundancy are worth the cost. This should be based on the reliability of the terminal equipment versus the possible revenue and goodwill loss.

3.4.2 For complete redundancy, a minimum of four single mode optical fibers should be provided. This provides one fiber for each transmission direction for both the active and standby systems. This arrangement provides 100% protection in the event of terminal equipment, splice, or connector failure. However, the efficacy of such an approach is questionable for mechanically damaged cable. When mechanical damage occurs to the fiber optic cable, it is highly likely that all the fibers in the cable will be damaged. Therefore, using fibers in the same cable for redundancy provides very little, if any, protection in the event of mechanical damage. The system design can use diverse routing to ensure total protection. Diverse routing provides protection through physical separation of the active and standby fibers, e.g., separate cables in trenches on opposite sides of the road. Another method that a designer can use to provide protection against total outages in certain situations is the "ring" routing layout. Section 3 describes the ring configuration.

3.4.3 Another method of diverse routing is the use of the existing copper plant as an alternative route in the event of lightwave terminal equipment or fiber cable failure. With this method, however, it should be kept in mind that reduced traffic capacity may result upon transfer to the copper facility.

3.4.4 Obviously, the provision of diverse routing can be quite expensive. It is, therefore, important to weigh the cost of the protection against the probability of failure and resultant loss of revenue. This is important regardless of the type of protection under consideration.

3.5 <u>Terminal Equipment Characteristics</u>

3.5.1 When designing a lightwave link, it is necessary to choose the type of transmitter and receiver to be used. The decision whether to use a LASER or LED source and an APD or PIN detector should be based on a combination of economic and technical considerations. If sufficient system gain is available using an LED source and a PIN detector, there are no compelling reasons to specify the more expensive LASER/APD combination.

3.5.2 Most lightwave transmission systems available today operate at a wavelength near 1310 nanometers. Some of these also will operate around 830 nanometers. The major reason for the use of a longer wavelength is to enable transmission over a longer link without the necessity for regeneration.

3.5.3 If a particular system will operate satisfactorily for a given application at the shorter wavelength, there is no technical reason to specify the more expensive longer wavelength. This also holds true for systems that can operate at either 1310 or 1550 nanometers.

3.6 <u>System Design</u>

3.6.1 Most current rural lightwave applications consist of direct point-to-point links between central offices or between hosts and remote units (RST, carrier, or concentrator). The design procedure for such cases is rather straightforward.

3.6.2 As mentioned previously, if the fiber's individual characteristics are sufficient, the characteristics of the terminal devices are the sole determination of the transmission capacity of the link. Traffic requirements determine the necessary optical data rate. The required system gain is directly proportional to the length of the link.

3.6.3 As an example of this situation consider the case of office A connected to office B via a lightwave link. The traffic requirements of the link, i.e., the number of channels required, normally determine the bit rate requirement for the lightwave terminal system. It is necessary to consider both the initial channel requirements and those in the future. For example, if the initial channel requirements can be met with a 45 Mb/s system but future traffic would require a higher bit rate system, several design methods could be considered.

3.6.4 Several philosophies can be used to provide the requirements of this design. A higher rate system, e.g., 90, 135, or 150 Mb/s, could be provided. Initially, the lightwave terminal contains only the number of low speed interface cards required to carry the initially supplied traffic. Additional cards can be furnished as required. A second alternative would be to purchase a system that can be initially arranged as a 45 Mb/s system and changed to a higher rate as traffic growth warrants. Again, the terminal contains only the initially required hardware. A third method is to equip a 45 Mb/s system initially and change it out to a higher rate system when required.

3.6.5 Furnishing the higher rate system initially requires a larger initial cash outlay and the telco wastes money if the higher traffic never materializes. Purchasing the 45 Mb/s system initially with the idea of changing out to a higher rate system if traffic ever warrants is the most expensive method if the higher traffic materializes. The purchase of a system that can be equipped as a 45 Mb/s system initially and can be changed to a higher rate while still in service may be the most practicable option in situations where future growth cannot be easily predicted.

3.6.6 The determination of whether or not a particular lightwave system will provide adequate operation from a transmission standpoint requires a link loss budget calculation. There are numerous methods of making this calculation but generally it consists of summing all losses in the link and comparing the result with the system gain (transmitter output minus receiver sensitivity). If the gain is greater than the cumulative losses, the system will normally operate satisfactorily. Generally, for short links the gain will be considerably greater than the loss. In such cases, attenuation must be added to the link to ensure proper operation. Since it is necessary to select both transmitters and receivers for specific applications, the optical signal levels that these devices must generate or operate satisfactorily with must be established and specified. Later paragraphs provide procedures and examples of link design.

3.6.7 It is important to note that the method used to design paired cable plant should be largely disregarded in fiber optic system design. This is the case because the traffic capacity of a fiber cable has little to do with the number of fibers that make up the cable. The capacity is largely dependent upon the electronics of the terminal equipment, e.g., the bit rate. For most current rural applications, four (4) fibers are sufficient (one for each transmission direction for the active and standby systems or two (2) spares for unprotected systems). A decision to provide additional "dark" fibers for "future use" should be carefully arrived at since it is generally possible to squeeze a very large capacity from fewer fibers by using terminal equipment with higher bit rates. A present worth analysis should be made whenever a system design includes "dark" fibers.

3.6.8 Although this section deals mainly with the design of a fiber optic link on a point-to-point basis, it should be kept in mind that overall system design must be considered in order to ensure satisfactory performance with lowest costs.

3.7 <u>Optical Link Design</u>

3.7.1 The unit used to express the output of a lightwave transmitter (source) coupled into the optical fiber is normally dBm or dB referenced to 1 milliwatt where 0 dBm = 1 milliwatt.

3.7.2 The Bit Error Rate (BER) of a lightwave receiver (detector) defines the quality of the electrical output signal for a specified optical input signal. This quality is the receiver sensitivity.

3.7.3 For example, a typical receiver input specification might specify that for a BER of 10^{-9}, the minimum receiver input level must be -40.5 dBm. In other words, for an input level of -40.5 dBm or higher, the BER of the electrical output of the receiver will be 10^{-9} or better except as noted in the following paragraph.

3.7.4 It is also possible for the quality of the electrical output signal of the receiver to be degraded if the optical input level is too high. Most manufacturers specify the maximum input signal level that will maintain the specified sensitivity. The specifications also can provide an additional parameter, the dynamic range which is the difference between the maximum and minimum input levels for which the manufacturer guarantees a given BER.

3.7.5 When the optical input signal level causes the receiver to be overdriven making the BER unsatisfactory, the receiver input level must be reduced. This reduction can be brought about by decreasing the transmitter output or by introducing optical attenuation into the link.

3.7.6 If the system has an acceptable BER and the receiver specifications are such as to ensure that that BER can be maintained, a satisfactory link can be designed including the selection of a transmitter with an appropriate output signal capability.

3.7.7 In addition, if the designer knows the transmission loss of the interconnecting fiber, the designer can determine the required optical output of the transmitter.

3.7.8 The loss in a lightwave link is not only caused by the optical fiber. Splices used to join lengths of fiber and mechanical connectors that connect fiber to terminal equipment also contribute to the total loss. Additionally, the loss introduced by WDM couplers, either installed initially or planned for future installation, must be considered in the original link design.

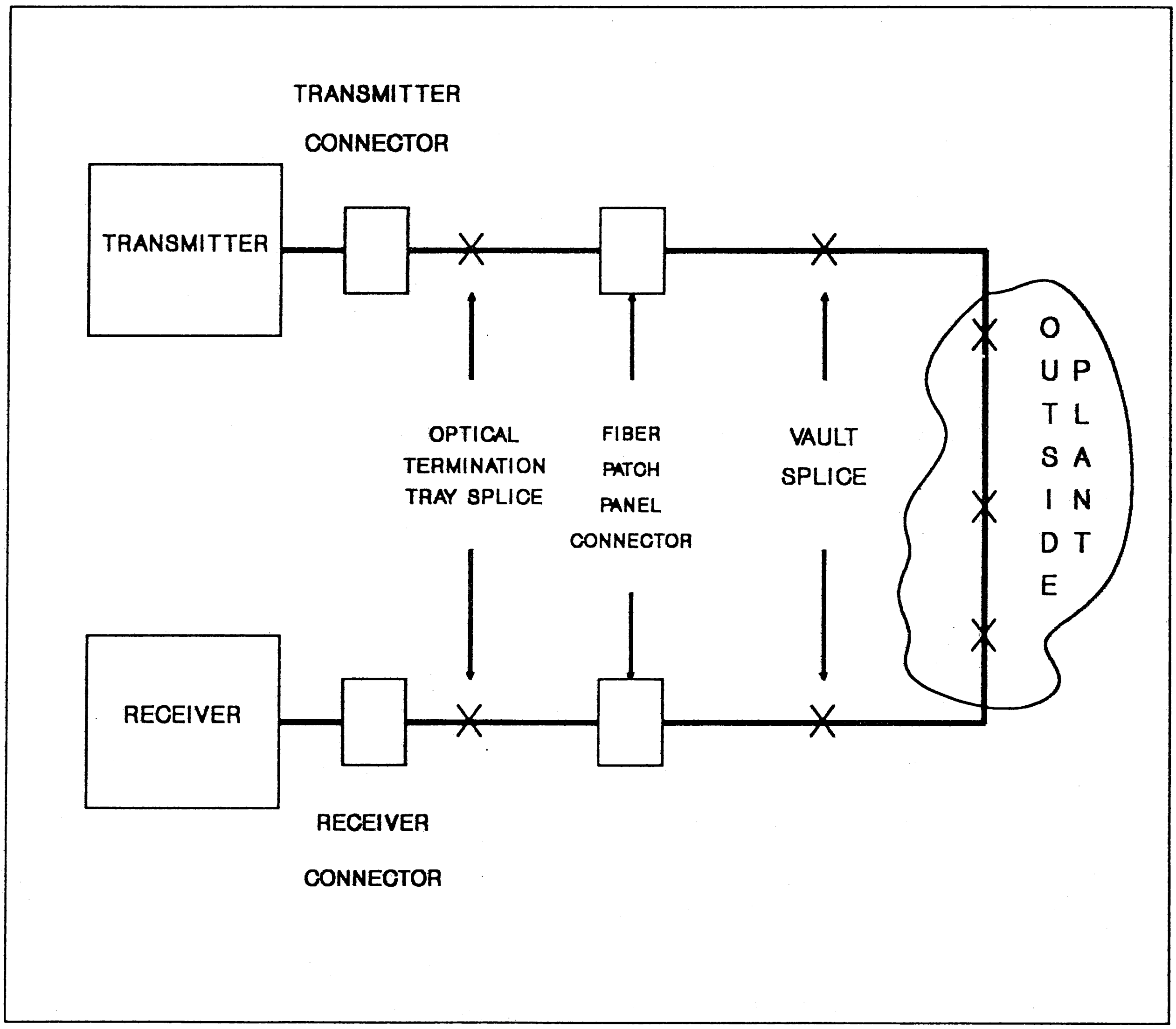
3.7.9 Besides the splices required to connect standard cable lengths, it should be anticipated that a certain number of additional splices will be required for maintenance purposes, e.g., to repair mechanical damage. The estimated additional loss contributed by these splices must be included in the original design.

3.7.10 It is also prudent to include a safety margin (commonly called a system margin) to account for other possible link losses caused by such factors as temperature variations, equipment aging, etc.

3.7.11 A link loss budget for the design of a satisfactory lightwave link includes all the factors mentioned in the previous paragraphs.

3.7.12 Figure 3-1 illustrates the typical configuration of a lightwave link. For simplicity, the figure shows this link comprised of a transmitter at one end and a receiver at the other. This figure shows the typical connectors and splices uses in a fiber optic link. It does not show WDM couplers normally connected at patch panels.

FIGURE 3-1
TYPICAL LIGHTWAVE LINK



3.7.13 The following typical numbers can be utilized in the formulation of the link loss budget when the designer does not know the actual figures.

3.7.13.1 A typical optical connector used to join fibers introduces a transmission loss of approximately 1 dB.

3.7.13.2 In general, a splice used to connect fiber ends introduces about 0.2 dB of loss for single mode fiber and 0.4 dB for multimode. If the designer does not know the exact number of splices required for construction of the link, the following formula can be used.

$$N = (L/RL) + 1 + E$$

where N = Actual number of required splices
L = Span Length
RL = Reeled cable length

If the designer does not know the actual reeled length, the designer may use the following figures for RL:

1.5 km (1 mile) for ducted cable
3.0 km (2 miles) for aerial cable
5.0 km (3 miles) for buried cable

E = Number of extra splices required by configuration of the physical outside plant, e.g., aerial to buried transition, patch panel splice, vault splice, etc.

3.7.13.3 WDM couplers introduce losses on the order of 3 dB.

3.7.13.4 The designer can reasonably use a system margin of 3 to 6 dB.

3.8 Typical Design Procedures

3.8.1 The following paragraphs provide a typical step-by-step procedure that can be used to design a lightwave system.

3.8.1.1 Determine the points to be connected.

3.8.1.1.1 How many DS1 circuits does the system require between these points?

3.8.1.2 Will the system use WDM initially or in the future?

3.8.1.3 What type of protection switching (low and high speed) will be used? (None, 1X1, 1XN)

3.8.1.4 What type of multiplex equipment, if any, does the system require?

3.8.1.5 What type of optical cross-connection does the system require? (optical fibers, WDM couplers, optical attenuators, etc.)

3.8.1.6 What type of electrical cross-connection does the system require? (DS1, DS2, DS3, etc.)

3.8.1.7 Make the link loss budget calculation.

3.8.1.7.1 If the system gain is greater than the total link loss including the system margin, the system does not require a repeater.

3.8.1.7.2 If the system gain exceeds the total link loss including the system margin by more than the dynamic range of the receiver, optical attenuation may be required.

3.8.1.8 Determine the heat dissipation, power drain, and floor loading of the selected system.

3.9 <u>Link Loss Budget Examples</u>

3.9.1 The information that can be obtained from a link loss budget is dependent upon the initially known link parameters. The following examples illustrate several different uses for the link loss budget.

3.9.1.1 Example 1 assumes the following known parameters.

Transmitter Output = -1.5 dBm
Receiver Sensitivity = -32 dBm
Link Length = 25 km
Number of Splices = 15 0.2 dB/splice = 3 dB
Number of Maintenance Splices = 10 0.2 dB/splice = 2 dB
Transmitter Connector Loss = 1 dB
Receiver Connector Loss = 1 dB
Patch Panel Connector Loss = 2 dB
System Margin = 5 dB

3.9.1.2 Using the above information it is possible to calculate the acceptable fiber loss as shown in Table 3-1.

3.9.1.3 The System Gain is the difference between the Transmitter Output and the Receiver Sensitivity [-1.5 -(-32) = 30.5 dB].

3.9.1.4 The Total Link Loss (excluding the fiber loss) is the sum of the losses associated with the splices, the connectors and the System Margin (3 + 2 + 4 + 5 = 14 dB).

3.9.1.5 The Acceptable Fiber Loss is the difference between the System Gain and the Total Link Loss (30.5 - 14 = 16.5 dB).

3.9.1.6 From the acceptable fiber loss figure it is possible to determine the maximum loss per unit length of fiber that would be satisfactory for this link (16.5/25 = 0.66 dB/km).

3.9.2 The fiber optic link in Example 2 has the following known parameters.

Link Length = 20 kilometers
Fiber Loss = .75 dB/km x 20 km = 15 dB
10 Splices 0.2 dB/splice = 2 dB
5 Maintenance Splices 0.2 dB/splice = 1 dB
Transmitter Connector Loss = 1 dB
Receiver Connector Loss = 1 dB
Patch Panel Connector Loss = 2 dB
System Margin = 5 dB

3.9.2.1 From the above parameters it is possible to calculate the System Gain required for proper operation as shown in Table 3-2.

3.9.2.2 The total link loss can be determined by summing the fiber, splice, and connector losses and the System Margin (15 + 2 + 1 + 4 + 5 = 27 dB).

TABLE 3-1
EXAMPLE 1 - ACCEPTABLE FIBER LOSS/UNIT LENGTH CALCULATION

A. TRANSMITTER OUTPUT POWER			-1.5 dBm
B. RECEIVER SENSITIVITY			-32 dBm
C. SYSTEM GAIN (A - B)			30.5 dB
LINK LOSSES			
CONNECTORS	4	x 1.0 dB -	4 dB
SPLICES	15	x 0.2 dB -	3 dB
MAINTENANCE SPLICES	10	x 0.2 dB -	2 dB
WDM COUPLERS	___	x 1.5 dB -	___ dB
OTHER DEVICES	___	x ___ dB -	___ dB
SYSTEM MARGIN			5 dB
D. LINK LOSS SUB-TOTAL			14 dB
E. ACCEPTABLE FIBER LOSS (C - D)			16.5 dB
F. LINK LENGTH			25 km
G. MAX. ACCEPTABLE FIBER LOSS/UNIT LENGTH (E/F)			0.66 dB/km

3.9.2.3 Therefore, the System Gain must be equal to or greater than 27 dB. This means that the Transmitter Output of the chosen lightwave terminal must be at least 27 dB greater than the Receiver Sensitivity for proper operation.

TABLE 3-2
EXAMPLE 2 - REQUIRED SYSTEM GAIN CALCULATION

A. LINK LENGTH			20 km
B. FIBER LOSS/KILOMETER			0.75 dB/km
C. TOTAL FIBER LOSS (A x B)			15 dB
LINK LOSSES			
CONNECTORS	4	x 1.0 dB -	4 dB
SPLICES	10	x 0.2 dB -	2 dB
MAINTENANCE SPLICES	5	x 0.2 dB -	1 dB
WDM COUPLERS	___	x 1.5 dB -	___ dB
OTHER DEVICES	___	x ___ dB -	___ dB
SYSTEM MARGIN			5 dB
D. LINK LOSS SUB-TOTAL			12 dB
E. REQUIRED SYSTEM GAIN (C + D)			27 dB

3.9.3 Table 3-3 shows the link loss budget for Example 3. In this example the designer knows all the parameters shown in Table 3-3. Additionally, the designer knows that the dynamic range of the lightwave terminal receiver is 15 dB. It can be seen, therefore, that this link requires some optical attenuation for proper operation to be assured. This is the case because the difference between the System Gain and the total link loss (45 - 26.5 = 18.5) is greater than the dynamic range of the receiver. Without the additional loss provided by the attenuator, an unsatisfactory BER may be obtained.

TABLE 3-3
EXAMPLE 3 - REQUIRED RECEIVER DYNAMIC RANGE CALCULATION

A. TRANSMITTER OUTPUT POWER			0 dBm
B. RECEIVER SENSITIVITY			-45 dBm
C. SYSTEM GAIN (A - B)			45 dB
LINK LOSSES			
CONNECTORS	4 x 1.0 dB =		4 dB
SPLICES	15 x 0.2 dB =		3 dB
MAINTENANCE SPLICES	10 x 0.2 dB =		2 dB
WDM COUPLERS	___ x 1.5 dB =		___ dB
OTHER DEVICES	___ x ___ dB =		___ dB
SYSTEM MARGIN			5 dB
D. LINK LOSS SUB-TOTAL			14 dB
E. FIBER LOSS/KILOMETER			0.5 dB/km
F. LINK LENGTH		25 km	
G. TOTAL FIBER LOSS (E x F)			12.5 dB
H. TOTAL LINK LOSS (D + G)			26.5 dB
I. REQUIRED RECEIVER DYNAMIC RANGE (C - H)			18.5 dB

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4. SYNCHRONOUS TRANSMISSION METHODS - SYNTRAN AND SONET

4.1 General

4.1.1 This section provides REA borrowers and other interested parties with an introduction to synchronous transmission principles.

4.1.2 Increasing usage of optical fiber technology in interoffice, subscriber and private networks has spurred growth of DS3 signals in today's telecommunications industry. Access to and control of these DS3 signals and their individual DS0 and DS1 signals is important for protection switching in the event of disasters, circuit provisioning based on the time of day, day of week, and/or destination, customer-controlled reconfiguration (CCR), and rapid response to changing service demands.

4.1.3 Current asynchronous DS3 transmission does not lend itself well to these functions and requires a large amount of equipment such as back-to-back lightwave terminals, multiplexers and channel banks.

4.1.4 Synchronous transmission simplifies multiplexing. When signals all have the same rate, it is easy to put them together and transport them at a higher rate. The lower rate signals are also directly identifiable within the higher rate structure. This allows for efficient drop and insert (add/drop) systems, digital cross-connect (DCS) equipment and digital switch interface.

4.1.5 Standardized synchronous transmission formats permit direct optical interface (mid-span meet) of equipment of different manufacturers.

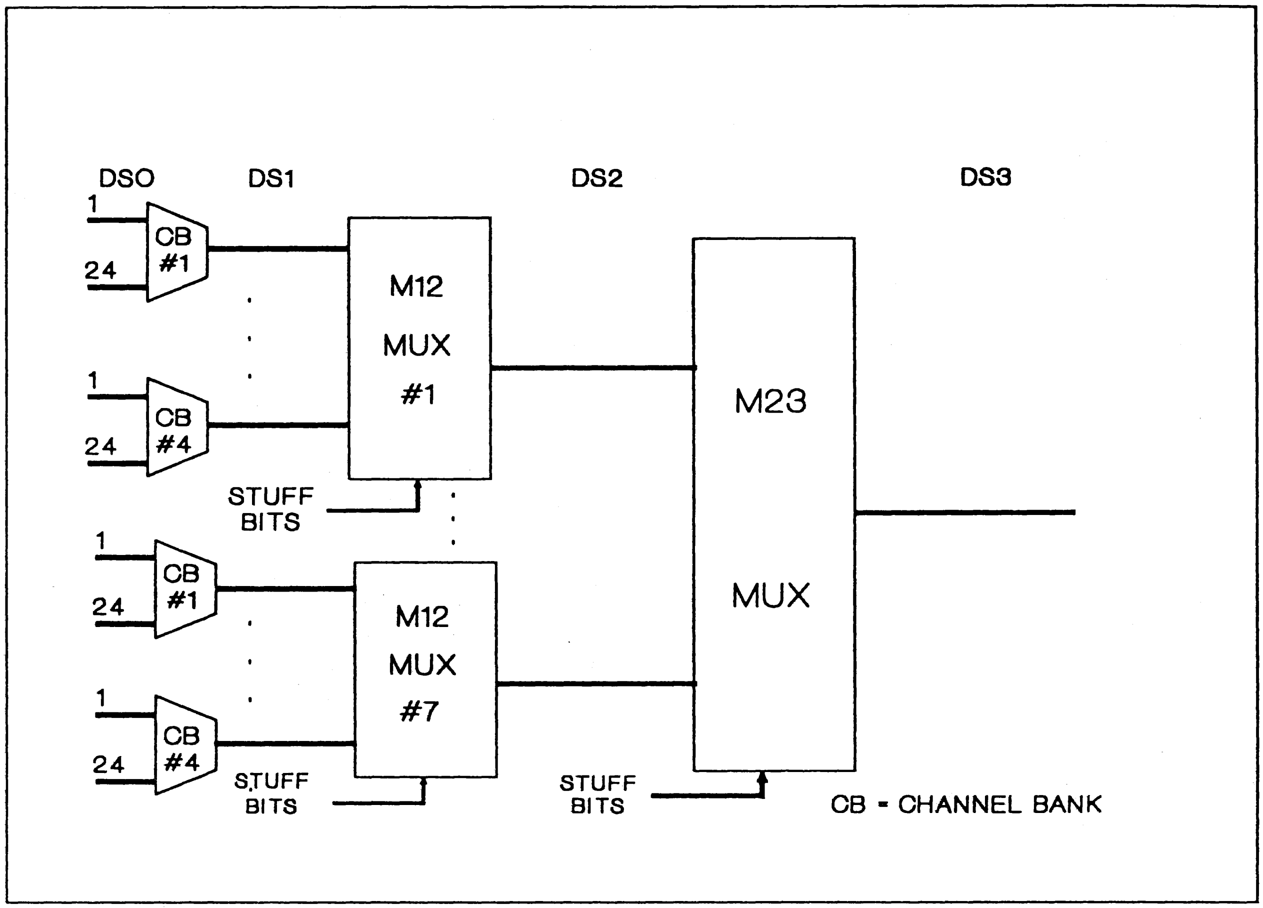
4.1.6 This section describes two defined synchronous transmission methods: SYNTRAN and SONET. These standardized methods provide direct access to the DS0 and DS1 signals that make up the DS3 signals.

4.2 Asynchronous DS3 Transmission

4.2.1 The traditional asynchronous DS3 bit stream consists of 28 multiplexed DS1 signals. The lightwave terminal first multiplexes these DS1s in groups of 4 into DS2 signals. The terminal then multiplexes these DS2 signals into a DS3 bit stream. Figure 4-1 shows the asynchronous M13 multiplexing scheme.

4.2.2 Since the source of each DS1 signal has a master clock operating at a slightly different rate and because of the different propagation delays of the various DS1s, the data rate of each of the incoming DS1 bit streams will be somewhat different. To synchronize these incoming signals the lightwave terminal writes the incoming digits of each DS1 into an elastic store (data buffer) under the control of the incoming signal clock of the individual bit streams. The terminal then reads the bits out of the buffer under the control of an independent local clock. This local clock operates at a faster rate than the incoming clocks that are nominally 1.544 Mb/s (but can vary ± 32 parts per million).

FIGURE 4-1
ASYNCHRONOUS M13 DIGITAL MULTIPLEXING



4.2.3 In order to synchronize the incoming DS1 signals, the lightwave terminal adds extra bits called stuffing bits or pulses to the bit streams at pre-arranged times. The terminal inserts these bits when the phase difference between the read and write clocks reaches a certain threshold. The signal includes stuff indicator bits to tell the far end terminal equipment that the incoming signal includes a stuff bit.

4.2.4 The multiplexing of the DS2 signals into the DS3 bit stream follows this same procedure.

4.2.5 The asynchronous DS3 signal makes it difficult to access the lower rate signals directly, i.e., DS0, DS1, without demultiplexing the entire DS3 signal. Additionally, there is minimal overhead available for network management and no compatibility among asynchronous lightwave transmission equipment of different suppliers.

4.3 <u>SYNTRAN Basics</u>

4.3.1 SYNTRAN, an acronym for <u>Syn</u>chronous <u>Tran</u>smission, is a standardized DS3 signal format restructured for synchronous transmission at 44.736 Mb/s. The SYNTRAN format is compatible with existing DS3 transmission facilities such as fiberoptic and digital radio systems.

4.3.2 SYNTRAN provides several advantages over the asynchronous DS3 format. For example, SYNTRAN provides immediate identification and direct access to all DS0 and DS1 signals which make up the SYNTRAN signal. This simplifies drop/insert and timeslot interchange functions.

4.3.3 Since the SYNTRAN format does not need certain bits required by the asynchronous DS3 signal, e.g., stuff bits and stuff indicator bits, these overhead bits can be used to provide other functions such as improved performance monitoring and control.

4.3.4 SYNTRAN is a one-step multiplexing scheme that eliminates an intermediate multiplexing stage required in the asynchronous DS3 format, i.e., the terminal equipment multiplexes 28 DS1 channels directly to the DS3 level bypassing the DS2 level. This allows less complex equipment design that leads to smaller, more efficient equipment packaging.

4.3.5 American National Standards Institute (ANSI) specification T1.103-1987[1] defines the SYNTRAN format.

4.3.6 Bellcore technical documents describe equipment designs using the SYNTRAN format for the following three network elements:

1. Add/Drop Multiplexer (TR-TSY-000010)[2]
2. Digital Cross-Connect System (TR-TSY-000233)[3]
3. Direct Digital Switch Interface (TA-TSY-000304)[4]

4.3.6.1 These documents specify features, functions, performance criteria, message formats, protocols, and commands required to ensure compatibility among various manufacturers' systems.

4.3.7 The SYNTRAN format includes two optional modes of information transport:

a. Bit Synchronous
b. Byte Synchronous

4.3.7.1 When the application does not require access to the individual DS0 channels, bit synchronous operation can be used. This method transports each DS1 signal as a complete bundle. Functions such as timeslot interchange as provided by a DCS that need direct access to the DS0 signals require byte synchronous operation.

4.3.8 Although SYNTRAN based systems are currently in operation, the technology never gained widespread usage because most manufacturers decided to wait for SONET specifications to be completed to design synchronous transmission equipment. It is unlikely that additional SYNTRAN based systems will be designed.

4.4 <u>SONET Basics</u>

4.4.1 SONET, an acronym for <u>S</u>ynchronous <u>O</u>ptical <u>Net</u>work, is a family of transmission rates from 51.84 Mb/s to 13.22 Gb/s. The SONET format defines a standard optical interface signal and multiplexing hierarchy that provides compatibility among equipment of different manufacturers.

4.4.2 The basic SONET transmission rate (51.84 Mb/s) is Optical Carrier - 1 (OC-1). Higher level signals are integer multiples of OC-1 or N X 51.84 Mb/s where N is 1 to 255. However, currently only N = 1, 3, 9, 12, 18, 24, 36, and 48 are standard. Table 4-1 lists the standard OC levels, their line rates, and the equivalent DS1 and DS3 capacities.

TABLE 4-1
STANDARD OPTICAL CARRIER LEVELS, RATES, AND CAPACITIES

OC Level	Line Rate (Mb/s)	DS3 Capacity	DS1 Capacity	DS0 Channels
OC-1	51.84	1	28	672
OC-3	155.52	3	84	2016
OC-9	466.56	9	252	6048
OC-12	622.08	12	336	8064
OC-18	933.12	18	504	12096
OC-24	1244.16	24	672	16128
OC-36	1866.24	36	1008	24192
OC-48	2488.32	48	1344	32256

4.4.3 The electrical equivalent of OC-1 is the Synchronous Transport Signal - 1 (STS-1) that also has a rate of 51.84 Mb/s. The SONET specifications define the higher rate signals as STS-N with N as defined in paragraph 4.4.2 above.

4.4.3.1 Broadband ISDN services such as High Definition TV will require multiples of the STS-1 rate. The lightwave terminal maps such services into a payload called an STS-Nc (c meaning concatenated or linked together). The lightwave system multiplexes, switches, and transports the concatenated payload as a single entity.

4.4.4 Both the DS0 and DS1 signals maintain visibility within the STS-1 level signal. That is, the terminal equipment knows the exact location of each DS0 and DS1 signal within the STS-1. This enables convenient manipulation of the signals for cross-connection, drop and insert, etc., without the necessity for demultiplexing the entire STS-1 signal.

4.4.5 SONET has the following advantages over asynchronous transmission methods:

a. Provides standard interfaces;
b. Provides single step multiplexing and demultiplexing;
c. Transports synchronous and asynchronous information;
d. Ensures compatibility among manufacturers;
e. Transports signals of various bandwidths;
f. Provides an intelligent maintenance network;
g. Reduces equipment costs.

4.4.6 The ANSI T1 Committee is developing the SONET specification in phases. Phase 1 consists of ANSI T1.105-1988[5] and T1.106-1988[6] that establish standards for items such as the signal format, multiplexing techniques and signal mapping. The T1 Committee has not yet finalized Phase 2, which is a revision of [5]. Phase 2 adds to and clarifies Phase 1 in the areas of timing and synchronization, automatic protection switching and data communications channels (DCC). Additional phases will be necessary to define various network management functions including messages to be used in the DCC. Ring protection switching and STS electrical specifications also require further standardization.

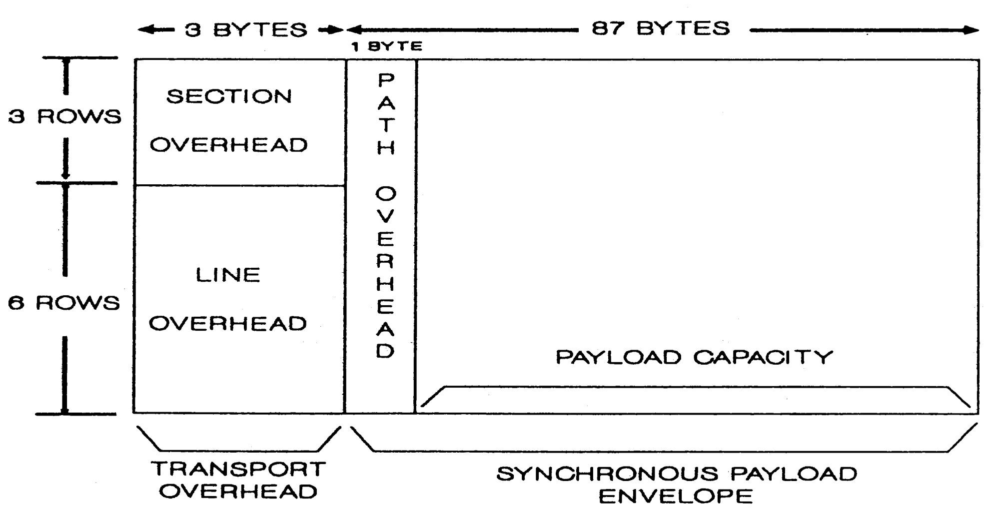
4.4.7 Until the T1 Committee completes the SONET specification, equipment of different manufacturers will not be totally compatible. It will be possible for certain information to be sent between different manufacturers' terminals, but operations information such as error monitoring information will not be able to be transferred because the messages will not be standard.

4.5 Structure of the SONET Signal

4.5.1 Figure 4-2 shows the frame structure of the STS-1 signal. This frame consists of 90 columns and 9 rows of 8-bit bytes for a total of 810 bytes or 6480 bits. Since the frame length is 125 microseconds, the STS-1 bit rate is 51.84 Mb/s (6480 bits/125 microseconds).

4.5.2 In Figure 4-2 the first three columns (27 bytes) of the STS-1 frame contain the Transport Overhead. This overhead consists of the Section Overhead (9 bytes) and the Line Overhead (18 bytes). Later paragraphs discuss the Transport Overhead in more detail. The remaining 87 columns (783 bytes) of the STS-1 frame form the Synchronous Payload Envelope (SPE). The first column of the SPE contains the STS Path Overhead (9 bytes) which later paragraphs discuss. The remaining 774 bytes of the SPE transport the STS payload.

**FIGURE 4-2
STS-1 FRAME**



4.5.3 The SPE is the portion of the STS-1 frame that contains the transported signal or service. This signal can be a DS3 or a group of DS1s, for example.

The SONET interface is flexible so that not only current standard digital signals can be transported but also as yet undefined future signals and services.

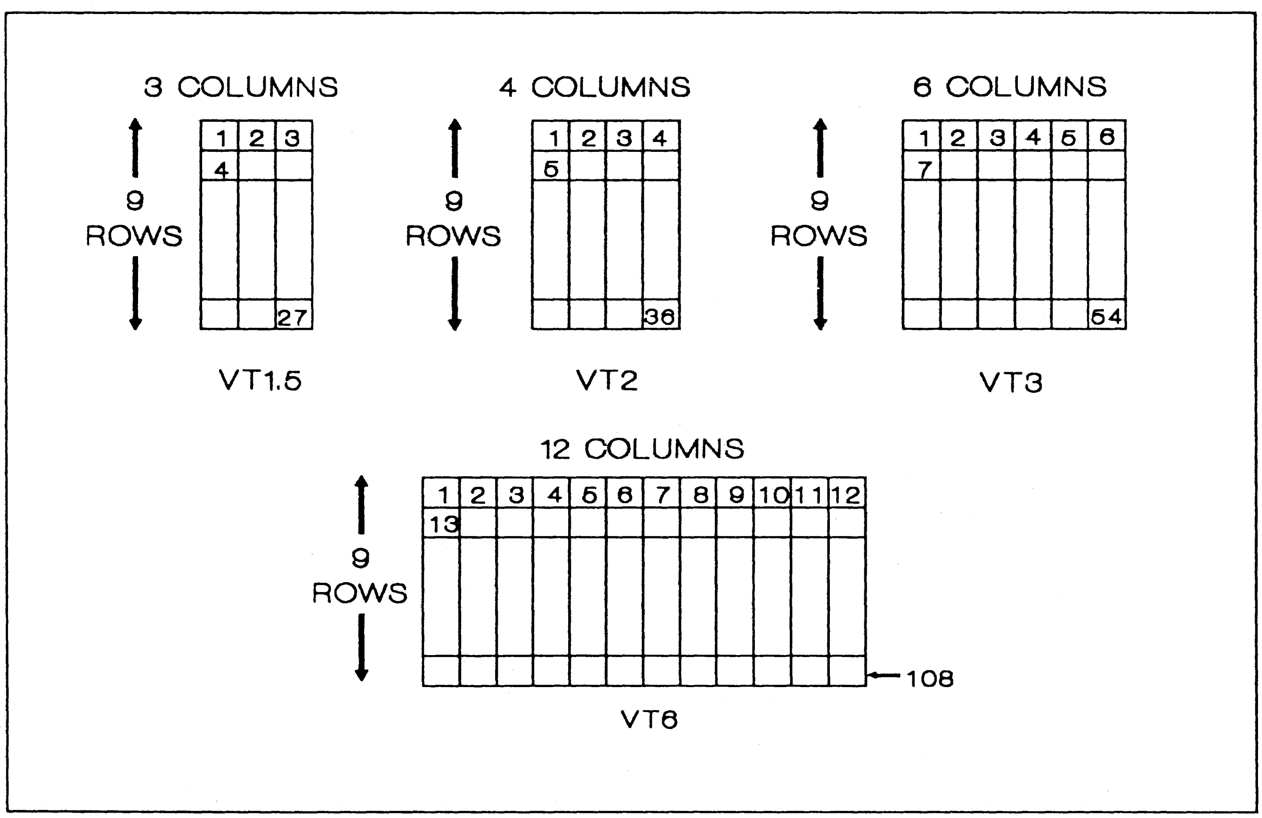
4.5.4 The SPE directly carries a DS3 signal transported in an STS-1. Structures (groups of bytes) called Virtual Tributaries (VT) carry DS1, DS1C, and DS2 signals. This VT structure enables direct identification of the signals within the STS-1 frame. This allows cross-connection and drop/insert functions without the necessity for demultiplexing the DS3 signal.

4.5.5 Figure 4-3 illustrates the Virtual Tributary structures. There are four sizes of VTs: VT1.5, VT2, VT3, and VT6. The VTs consists of 9 rows by 3 columns (27 bytes) for VT1.5, 4 columns (36 bytes) for VT2, 6 columns (54 bytes) for VT3, and 12 columns (108 bytes) for VT6. These VT structures transport the following payloads:

VT1.5	DS1
VT2	CEPT1 *
VT3	DS1C
VT6	DS2

* European E1 standard (2.048 Mb/s)

FIGURE 4-3
VIRTUAL TRIBUTARIES



4.5.6 The terminal equipment places the VTs in the STS-1 SPE in 7 VT groups. Each of these VT groups consists of 12 columns of the 9-row SPE structure.

This fills 84 of the 87 columns available in the SPE. The terminal fills the remaining three columns with fixed stuff bytes that carry no valid information. Since each VT group consists of 12 columns of the SPE, each VT group may contain 4 VT1.5s, 3 VT2s, 2 VT3s, or 1 VT6. Each VT group may consist of only one VT size, but the SPE may consist of VT groups of any combination of the different VT sizes.

4.5.6.1 There are two possible modes of operation of the VT structure. In the Locked Mode the terminal uses fixed mapping of the synchronous VT payloads into the STS-1 SPE. Since direct access is available to the DS0 circuits, optimized switching is available at the DS0 rate. In the Floating Mode, VT payload mappings are flexible and dynamic within the STS-1 SPE. SONET terminal equipment use pointers to indicate the starting point of the VT payload. This mode minimizes the switching delay.

4.5.7 In order to obtain the higher rate STS-N signals, the lightwave terminal synchronously multiplexes the STS-1 signals. This means that all the STS-1s must have the same frequency. This could be accomplished as described in paragraph 4.2 but this would eliminate the advantages of synchronous transmission, e.g., direct identification of DS0 and DS1 signals, etc. The SONET specification defines a synchronous multiplexing method using pointers that eliminates problems such as delay, slips, and detection of synchronization failures encountered in previous multiplexing techniques.

4.5.8 Since system clocks at opposite ends of a transmission facility are not completely synchronous, the elastic stores will tend to overflow or underflow at times during the transmission. If this occurs, data would be lost as would framing. Reframing required throughout the network causes additional data to be lost.

4.5.9 A controlled slip, or simply, slip, is the deletion or repetition of a single frame of data. The terminal equipment introduces a slip when overflow or underflow is imminent. This adds or deletes data but maintains the framing. Slips normally do not bother voice transmission but may present problems for data circuits. Besides lost or added data, the terminal introduces delay each time it provides a slip.

4.5.10 The SONET STS-1 signal uses pointers to minimize the problems associated with slips. Pointers mark the beginning of the SPE within the STS-1 frame. If data enters the elastic store at too fast a rate, the terminal removes an extra byte and decrements the pointer by one. If data is entering the elastic store too slowly, the terminal repeats a special byte and increments the pointer by one. This method of synchronization does not entail the loss or repetition of data.

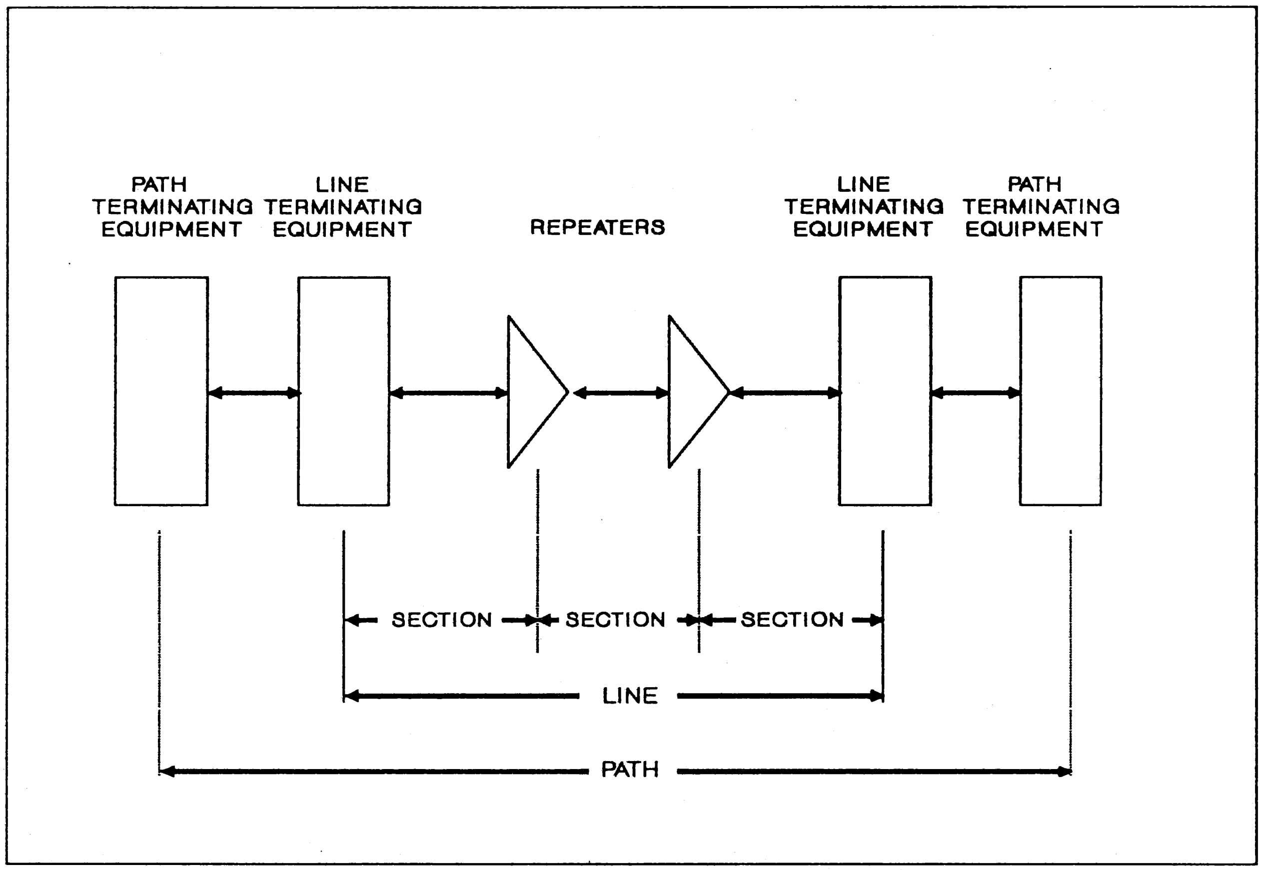
4.5.11 Using the slip method causes delay because a large number of bits must be stored to be able to repeat a frame of data. In the pointer method fewer bits need to be stored making the delay considerably smaller.

4.6 Overhead and Transport Layers

4.6.1 The terminal equipment assigns overhead and transport portions of the SONET signal to layers based on hardware and functional considerations. The four layers are Photonic, Section, Line, and Path. Figure 4-4 pictorially defines the Section, Line, and Path layers.

4.6.2 In the Photonic layer the lightwave terminal converts the STS signal to the OC signal and vice versa, i.e., electrical impulses converted to a light signal. This layer has no associated overhead. Electro-optical units such as transmitters and receivers are part of this layer. This layer deals with optical pulse shape, power levels and wavelength.

FIGURE 4-4
DEFINITIONS OF SECTION, LINE, AND PATH LAYERS



4.6.3 The Section layer includes that portion of the network between the line terminating equipment and a repeater or between repeaters. Functions of the Section layer include framing, scrambling, section error monitoring, and section overhead. This layer deals with the transport of the STS frame. A regenerator is an example of hardware associated with this layer.

4.6.4 The Line layer is the part of the network between line terminating equipment. This layer includes equipment that multiplexes STS-1 signals to higher rate STS-N signals and deals with the transport of the Path layer payload and its overhead. This layer provides synchronization and multiplexing for the Path layer. A multiplexer is an example of equipment in this layer.

4.6.5 The Path layer provides transport of services between Path Terminating Equipment, i.e., from local office to local office. DS1s, DS3s, and video signals are examples of such services. The main function of this layer is to format these services as required by the Line layer, i.e., the terminal creates and disassembles the STS-1 signals in this layer. A DS3 to STS-1 mapping circuit is an example of hardware in this layer.

4.6.6 The major advantage of the layer concept is that if the terminal constructs and transports the signal in the highest layer correctly, all the lower layers will deliver the signal without error. The optical interface layers defined previously interact with each other as described in the following paragraphs.

4.6.6.1 Network services carried by DS1 and DS3 signals are inputs to the Path layer. This layer transports these services and the Path Overhead between like equipment within the layer, e.g., fiber optic terminal to fiber optic terminal. The Path layer places (maps) the services and Path Overhead into SPEs and passes them to the Line layer.

4.6.6.2 The system transports the SPEs and Line Overhead between like equipment within the Line layer, e.g., multiplexers. The terminal equipment multiplexes the SPEs and Line Overhead into STS-N signals and passes them to the Section layer.

4.6.6.3 The Section layer transports the STS-N signals and Section Overhead between like equipment within the Section layer, e.g., regenerators. The lightwave terminal converts the STS-N signals and Section Overhead to electrical pulses and passes them to the Photonic layer for conversion to optical signals.

4.6.7 The following paragraphs give a brief description of the information available in the SONET overhead.

4.6.7.1 The Section Overhead contains the following information:

4.6.7.1.1 **Framing** - The terminal equipment uses two bytes to store a standard bit pattern that provides the framing for each STS-1 frame.

4.6.7.1.2 **STS-1 Identification** - This is a unique number assigned to each STS -1 frame that the terminal uses in framing and in breaking down STS-N signals into their components STS-1s.

4.6.7.1.3 **Section BIP-8** - The terminal equipment uses this Bit Interleaved Parity (BIP) information to provide section error monitoring. The terminal calculates this BIP using all the bits in the previous STS-N frame.

4.6.7.1.4 **Orderwire** - This provides a local orderwire channel reserved for voice communications between section terminating equipment, e.g., regenerators.

4.6.7.1.5 **Section User Channel** - The SONET specification reserves this channel for the user's purposes.

4.6.7.1.6 **Section Data Communication Channel** - This is a 192 kb/s channel used for alarms, maintenance, control, monitoring, administration, and other communications between section terminating equipment.

4.6.7.2 The following information can be found in the Line Overhead:

4.6.7.2.1 **Pointer** - The data indicates the beginning of the SPE within the STS-1 frame and provides frequency justification (synchronization) as described in paragraph 4.5.

4.6.7.2.2 **Pointer Action Byte** - The terminal uses this byte in frequency justification to carry valid information when the incoming data arrives too rapidly.

4.6.7.2.3 **Line BIP-8** - The terminal equipment uses this for line error monitoring. The terminal calculates this BIP using all the Line Overhead and STS-1 SPE of the previous STS-1 frame.

4.6.7.2.4 **APS Channel** - The terminal equipment uses this data for Automatic Protection Switching (APS) signaling between line layer elements.

4.6.7.2.5 **Line Data Communication Channel** - This is a 576 kb/s channel used for alarms, maintenance, control, monitoring, administration, and other communications between line terminating equipment.

4.6.7.2.6 **Growth** - The SONET specification reserves this overhead for future undefined functions.

4.6.7.2.7 **Orderwire** - This provides an express orderwire channel used for voice communications between line terminating equipment.

4.6.7.3 The STS Path Overhead includes the following information:

4.6.7.3.1 **Path Trace** - This is a repetitive fixed length string of bits used to verify the connection between a transmitter and a receiver.

4.6.7.3.2 **Path BIP-8** - The lightwave terminal uses this BIP for path error monitoring. The terminal calculates this BIP using all the bits of the previous STS SPE.

4.6.7.3.3 **Path Signal Label** - This information indicates the construction of the STS SPE, e.g., whether or not the system has equipped path terminating equipment.

4.6.7.3.4 **Path Status** - The terminal uses this information to transmit the status and performance of one end of the path to the other end.

4.6.7.3.5 **Path User Channel** - The SONET specification reserves this overhead for user communication between path elements.

4.6.7.3.6 **VT Multiframe Indicator** - Only VT-structured payloads use this. It contains the VT pointers and signaling for various payloads.

4.6.7.3.7 **Growth** - The SONET specification resrves this for future undefined uses.

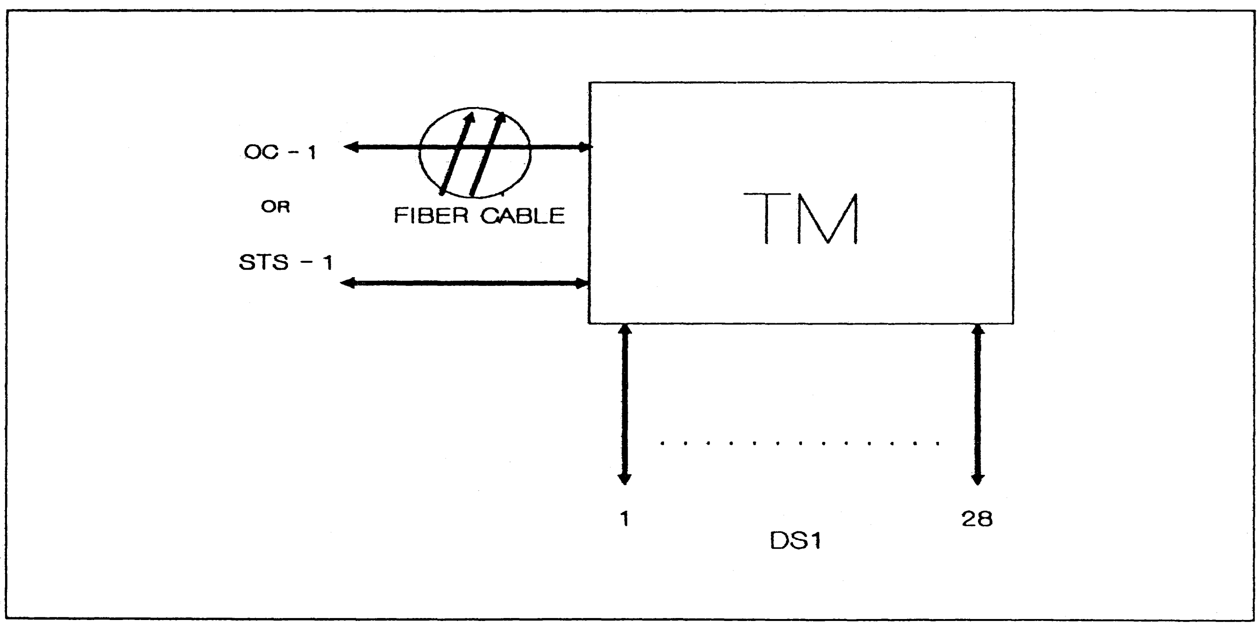
4.6.7.4 The VT Path Overhead provides error checking, signal label, and path status (equivalent functions as described previously for the STS Path Overhead).

4.7 <u>SONET Equipment</u>

4.7.1 The following paragraphs describe some of the SONET-based equipment that is available now or will be in the future. All manufacturers may not provide every equipment type mentioned, nor will every system provide all the features described.

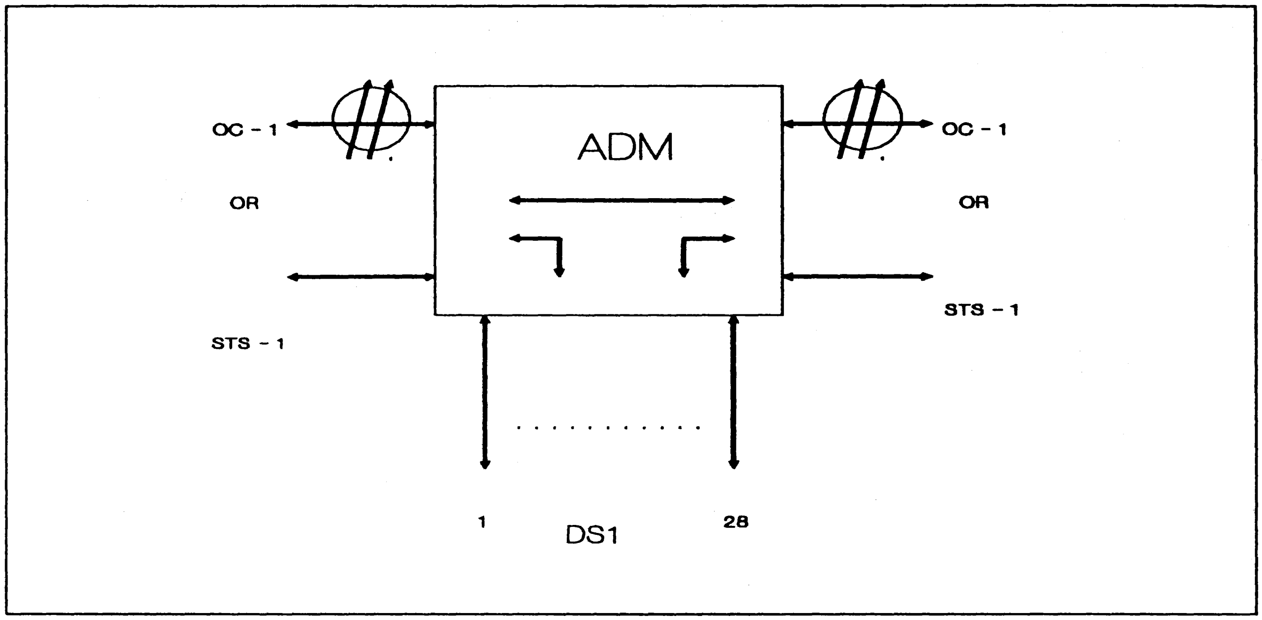
4.7.2 As shown in Figure 4-5, the Terminal Multiplexer (TM) provides an interface between an STS-1 or OC-1 port and up to 28 DS1 ports. DS1 grooming can be provided in that any of the 28 DS1s that make up the STS-1 (or OC-1) can be routed to any of the 28 DS1 ports. Initial TMs will operate at 51.84 Mb/s (OC-1) as described. Future models will be available for higher rates (STS-N/OC-N).

FIGURE 4-5
TERMINAL MULTIPLEXER (TM)



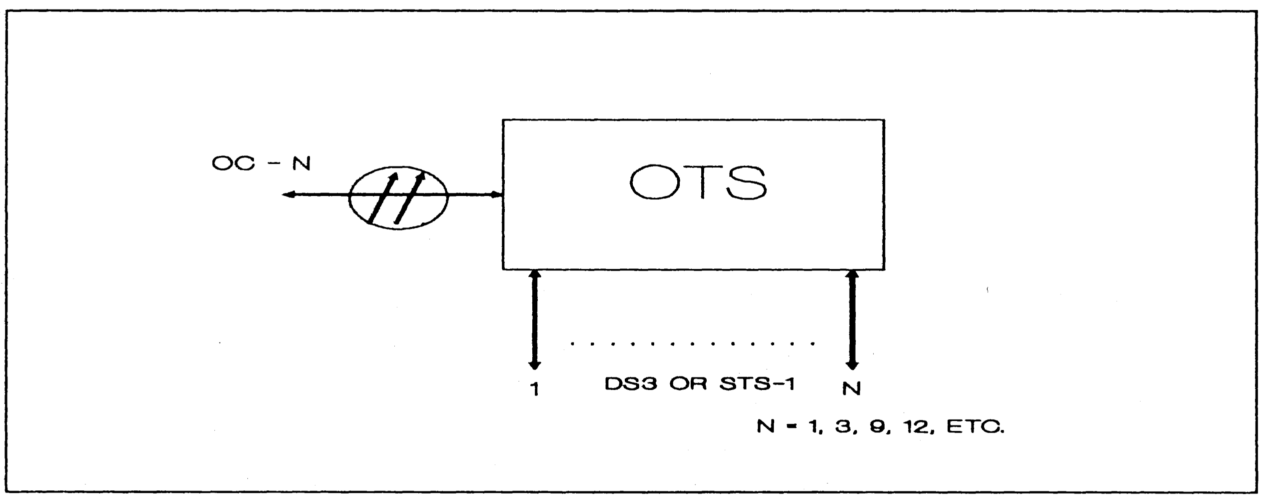
4.7.3 Figure 4-6 illustrates a SONET-based Add/Drop Multiplexer (ADM) as specified in Bellcore TR-TSY-000496[7]. Initial versions will operate at 51.84 Mb/s with later systems available at higher bit rates. The ADM high speed ports provide STS-1 or OC-1 interfaces while the low speed ports operate at DS1. The ADM can be arranged for DS1 and DS0 grooming. DS1 grooming allows any of the 28 DS1s in the STS-1 or OC-1 to be routed to any of the DS1 ports. DS0 grooming enables routing of any DS0 to any time slot of the STS-1 or OC-1. Additionally, any DS0 can be switched between DS0 ports or between the incoming and outgoing high speed ports.

FIGURE 4-6
ADD/DROP MULTIPLEXER (ADM)



4.7.4 Figure 4-7 shows a generalized SONET-based Optical Transport System (OTS). In this system the high speed optical interface is at OC-N and the low speed electrical interface can be DS3 or STS-1. There are a total of N low speed ports available that can be configured in any combination of DS3s and STS-1s. For example, for an OC-3 system three low speed ports would be available. These ports could be arranged as 3 DS3s or 3 STS-1s or any combination of the two.

FIGURE 4-7
OPTICAL TRANSPORT SYSTEM (OTS)



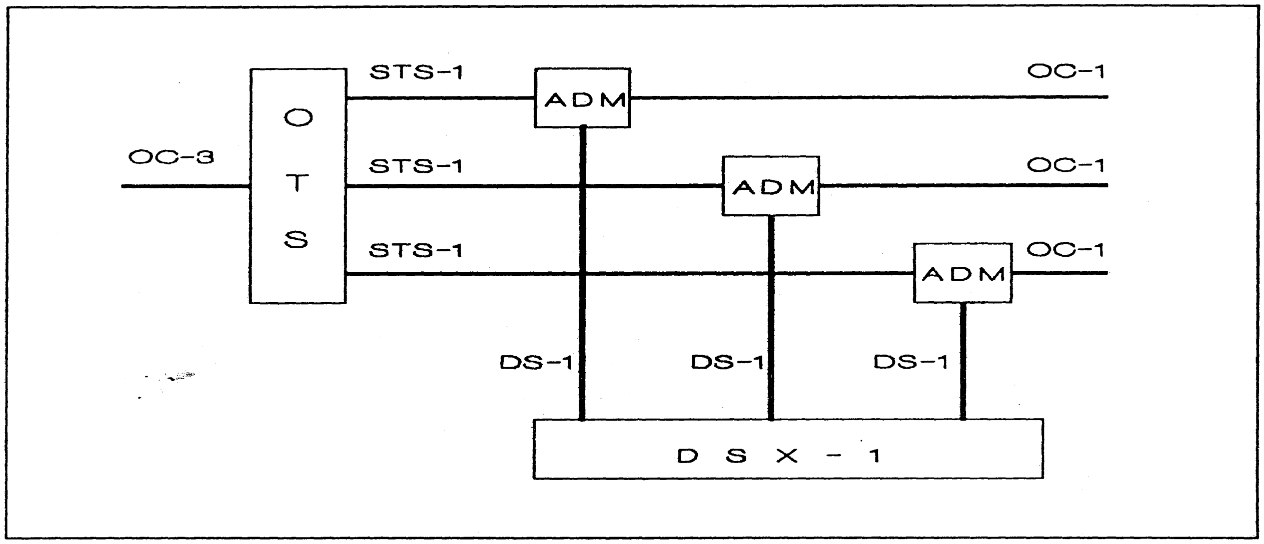
4.7.5 Besides the SONET-based lightwave equipment discussed in the previous paragraphs, other equipment types such as digital loop carrier (DLC), digital cross-connect systems (DCS), and digital central office equipment (Bellcore TR-TSY-000782)[8] have, or will have, SONET interfaces.

4.8 <u>SONET Applications</u>

4.8.1 The following paragraphs describe some of the applications in which SONET equipment can be used to advantage.

4.8.2 Figure 4-8 shows a hub configuration where an optical transmission system demultiplexes an OC-3 signal into three STS-1 signals for transport to three separate offices. The add/drop multiplexers include the local office in the network by dropping DS1 signals from the STS-1s and inserting DS1s into the STS-1s.

FIGURE 4-8
HUBBING

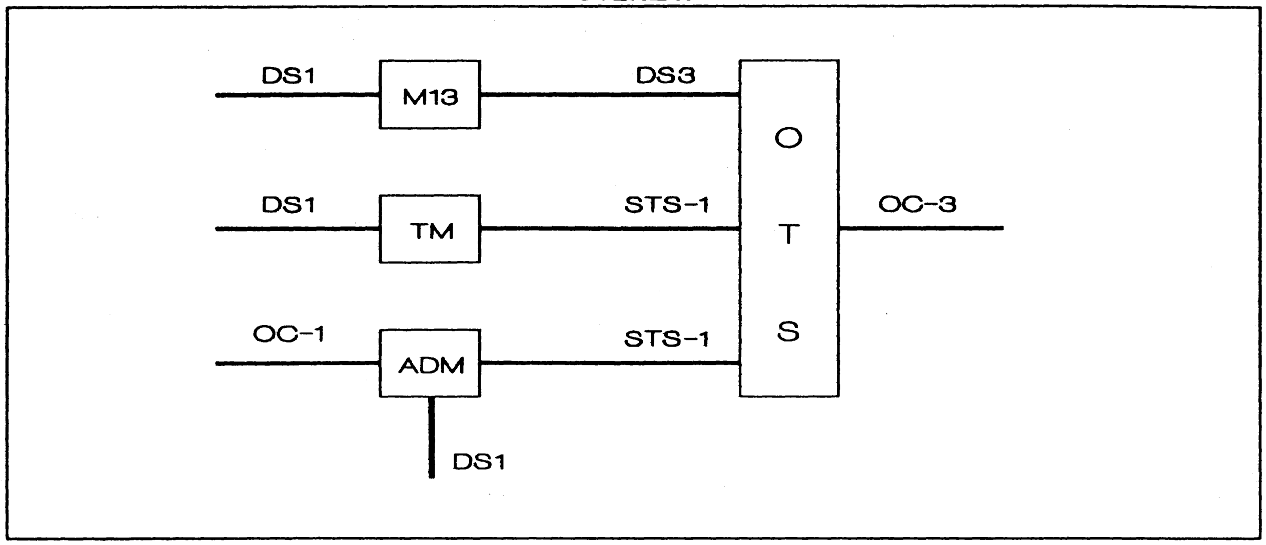


4.8.2.1 SONET allows remote reconfiguration of the network. Administration can be provided from a central location. Conventional design would require back-to-back multiplexers in addition to a lightwave transmission system at each ADM location.

4.8.2.2 Standardized special purpose channels called Embedded Operation Channels (EOC) can provide centralized automated maintenance, control, and test functions that previously had to be accomplished locally and manually. These remote control functions will aid in alarm management, circuit testing, network diagnostic procedures, and the dispatch of craftspersons to trouble locations.

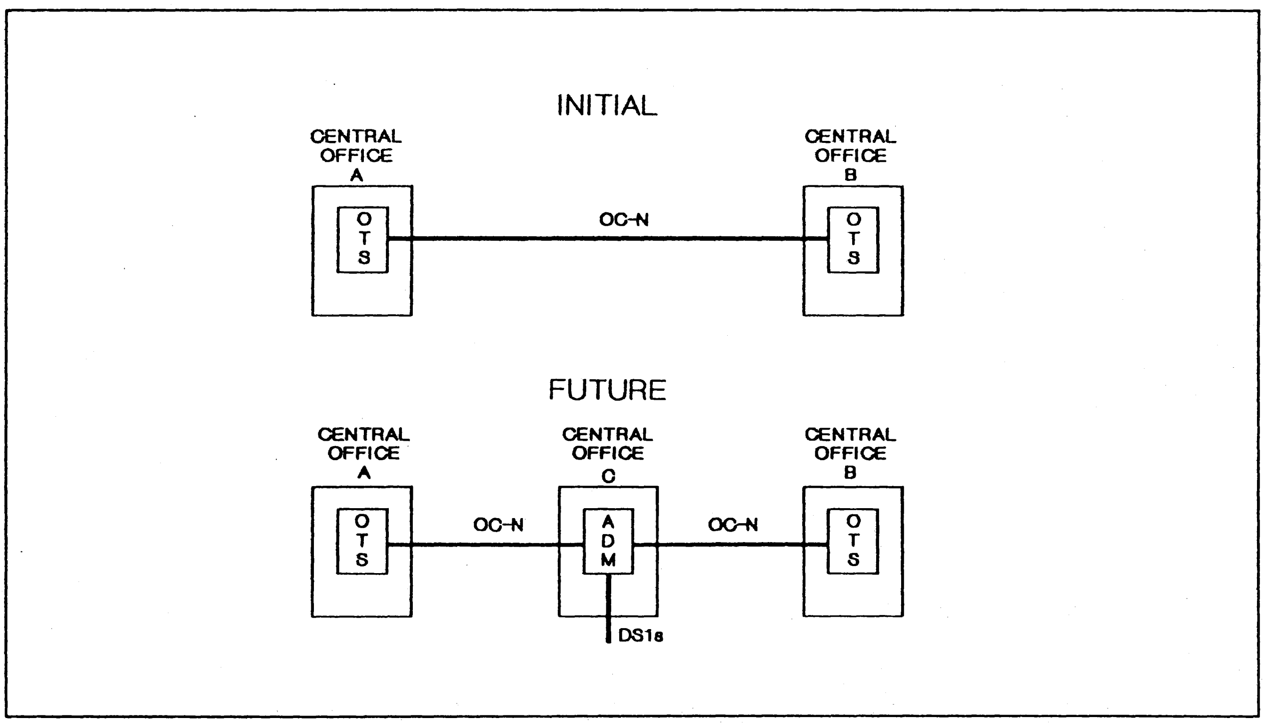
4.8.3 Figure 4-9 shows an example of an overlay application where the new SONET network includes a previously installed M13 multiplexer system.

FIGURE 4-9
OVERLAY



4.8.4 During the initial design phase as shown in Figure 4-10, SONET equipment connects central offices A and B. At that time the network planners expected future growth between the two offices, but when and exactly where was somewhat nebulous. When the growth occurs, an additional central office or other electronics such as a DLC can be placed as required as shown in Figure 4-10. The required lightwave equipment can be that of the same manufacturer as the original equipment or a different vendor.

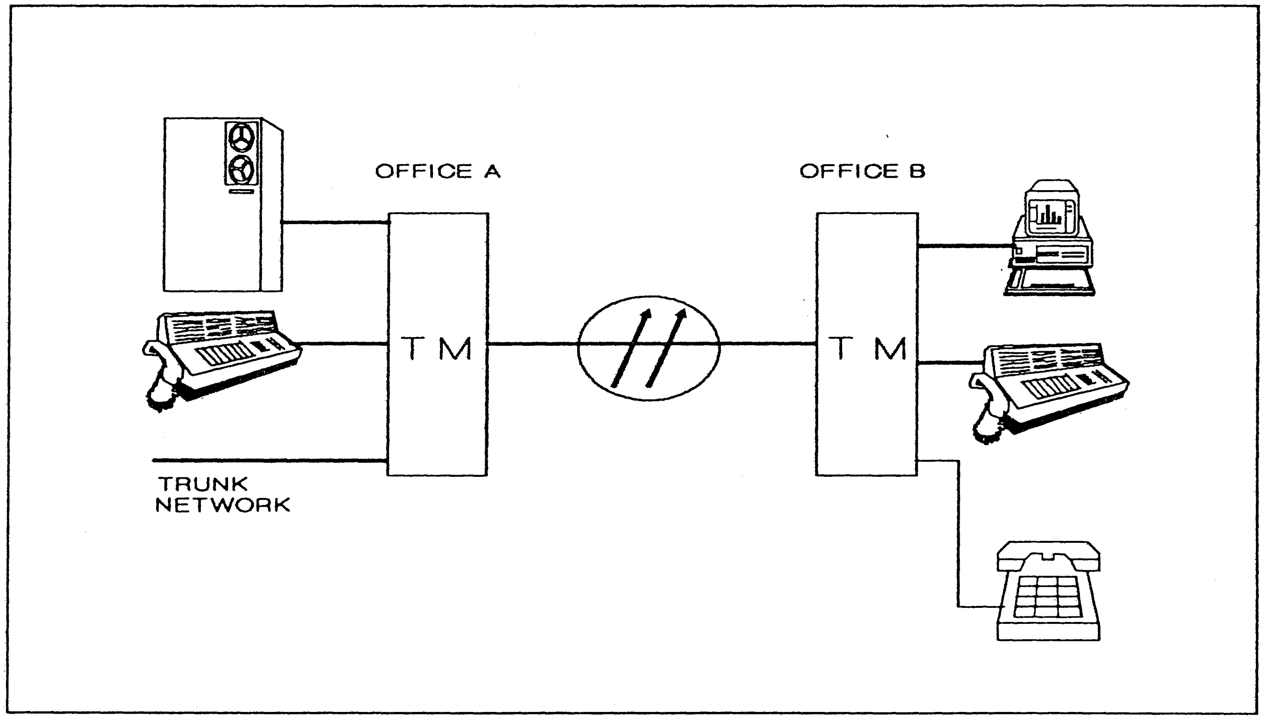
FIGURE 4-10
FUTURE EXPANSION



4.8.4.1 With the add/drop facility of SONET equipment, it is often possible to install fewer fibers initially. For example, in Figure 4-10, if asynchronous equipment were to be used, one design method would entail initially installing a lower bit rate lightwave system and spare fibers with the idea of adding another system after equipping office C . With SONET equipment it would be possible to drop channels easily at Office C from the same fibers used between Offices A and B. It would not be necessary to provide extra fibers initially.

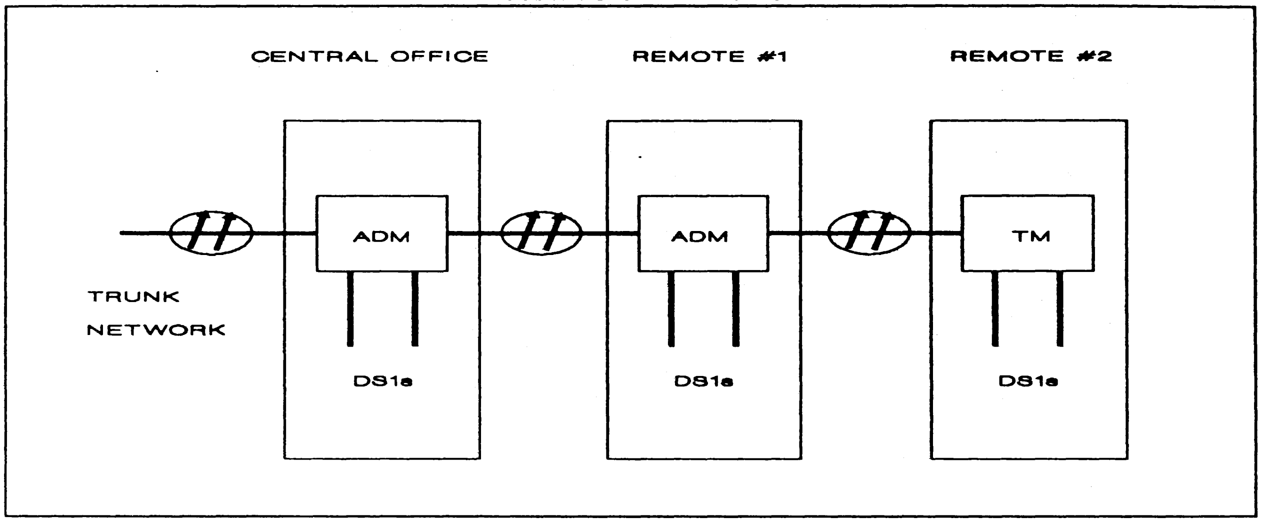
4.8.5 Figure 4-11 shows an example of DS1/DS0 grooming. In this example, the lightwave system connects traffic from a computer terminal, a PBX, and an ordinary telephone in office B to a mainframe, a PBX and the trunk network in office A. That is, the lightwave link connects (grooms) the DS1/DS0 traffic associated with the computer terminal in office B to the DS1/DS0 associated with the computer mainframe in office A. In a similar fashion, the lightwave link connects the PBX in office B to the PBX in office A and the telephone in office B to the trunk network in office A.

FIGURE 4-11
DS1/DS0 GROOMING



4.8.6 Figure 4-12 shows a feeder route using SONET-based equipment. This example illustrates how the system distributes traffic incoming over the trunk network among the central office and its two remote units. In addition, the lightwave system transports local traffic, i.e., between the central office and its remotes, via the same route.

FIGURE 4-12
FEEDER DISTRIBUTION



4.8.7 SONET-compatible equipment also lends itself well to various protection switching arrangements including ring networks as described in Section 3. The maintenance diagnostic capabilities built into the SONET overhead make protection switching very flexible and inexpensive.

4.9 References

[1] *Digital Hierarchy - Synchronous DS3 Format Specifications*, American National Standards Institute (ANSI), T1.103-1987

[2] *Synchronous DS3 Add-Drop Multiplex (ADM 3/X) Requirements and Objectives*, Bell Communications Research, TR-TSY-000010, Issue 1, February 1988

[3] *Wideband and Broadband Digital Cross-Connect Systems Generic Requirements and Objectives*, Bell Communications Research, TR-TSY-000233, Issue 1, September 1988

[4] *Synchronous DS3 Digital Switch Interface Requirements and Objectives*, Bell Communications Research, TA-TSY-000304, May 1988

[5] *Digital Hierarchy - Optical Interface Rates and Formats Specifications*, American National Standards Institute (ANSI), T1.105-1988

[6] *Digital Hierarchy - Optical Interface Specifications (Single Mode)*, American National Standards Institute (ANSI), T1.106-1988

[7] *SONET Add-Drop Multiplex Equipment (SONET ADM) Generic Requirements and Objectives*, Bell Communications Research, TR-TSY-000496, Issue 1, September 1988

[8] *SONET Digital Switch Interface Criteria*, Bell Communications Research, TR-TSY-000782, Issue 1, December 1988

5. LIGHTWAVE TERMINOLOGY

5.1. General

5.1.1 This section provides REA borrowers and other interested parties with a glossary of lightwave terminology.

5.1.2 This section provides a definition of the terms as they are most commonly used. This list is not all-inclusive but a compilation of the more commonly used lightwave terms. This section provides a useful reference for engineers and craftpersons to foster a better understanding of lightwave technology. It should be noted that some of the terms are not exclusive to lightwave. However, the definitions given are in terms of their lightwave usage.

5.1.3 The reader should reference Bulletin 1751H-403, *Digital Transmission Fundamentals*, for digital transmission terms also used in lightwave discussions.

5.1.4 It is not the intent of this section to provide complete or precise definitions.

GLOSSARY OF TERMS

A

ABSORPTION Signal attenuation caused by the conversion of light energy to heat. The reflections of the optical signals as they pass through the optical fiber cause this conversion.

ATTENUATION Reduction in signal strength along an optical fiber attributable to absorption and scattering. The units of this parameter are usually decibels per kilometer (dB/km).

AVALANCHE PHOTODIODE (APD) A semiconductor device that operates on the principle that hole-electron pairs created by absorbed photons acquire sufficient energy to create additional hole-electron pairs when they collide with substrate atoms (avalanche affect), thus creating current multiplication and signal gain.

B

BACKSCATTERING The diffusion of light rays such that portions of the rays return in a reverse (backward) direction. Impurities or discontinuities in the fiber core commonly cause backscattering.

BANDWIDTH Range of frequencies within which an optical fiber or terminal device is capable of transmitting data. Normally expressed in bits of information transmitted in a specific time period for a specific length of fiber, e.g., megabits/second/kilometer.

BIT The smallest unit of information handled by digital lightwave systems. Also, the optical pulse that carries the information.

BIT ERROR RATE (BER) The fraction of incorrectly received transmitted bits. The BER in lightwave systems is about a magnitude of 10^{-9}, i.e., one bit per billion incorrectly received transmitted bits.

C

CHROMATIC DISPERSION The combination of material dispersion and waveguide dispersion (wavelength dependent).

CLADDING The material with a lower index of refraction that surrounds the core of an optical fiber. This material causes the transmitted light to be reflected and travel down the core. (See Figure 1-3.)

COHERENT LIGHT Light in which the electromagnetic waves maintain a fixed phase relationship while traveling through an optical fiber.

CONE OF ACCEPTANCE The angular dispersion of light (twice the angle associated with the Numerical Aperture) within which all rays (modes) entering the optical fiber remain in the core of the fiber (total reflection).

CONE OF RADIATION The angular dispersion of light exiting the fiber end.

CONNECTOR A mechanical device that provides a non-permanent connection between optical fibers or between an optical fiber and a source or detector. This connection can be disconnected and reconnected to simplify replacement of the source or detector and to connect test equipment.

CORE The light conducting portion of an optical fiber made up of a material with a higher index of refraction that the surrounding cladding. (See Figure 1-3.)

COUPLER An optical device that can combine optical power from more than one input into one fiber or split optical power from one fiber into several outputs.

COUPLING EFFICIENCY The ratio of transmitted light energy to incident light energy as measured at a discrete junction in a fiber optic link, e.g., source to fiber, fiber to fiber, fiber to detector.

CRITICAL ANGLE The angle of the reflected ray in the optical fiber when the ray enters the core at the angle associated with the Numerical Aperture. All light rays (modes) striking the core-cladding junction at an angle less than the critical angle remain in the core of the fiber (total reflection) For angles greater than the critical angle, light rays refract through the cladding. (See Figure 1-3.)

CUTOFF WAVELENGTH The wavelength below which a single mode optical fiber ceases to be single mode, i.e., the fiber supports more than one mode.

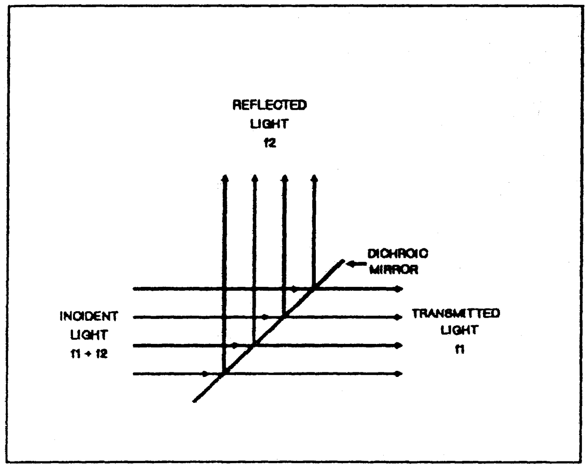
D

DARK CURRENT The electrical current that flows in a detector when there is no incident light. Also called leakage current.

DETECTOR A device used to receive the transmitted optical signal.

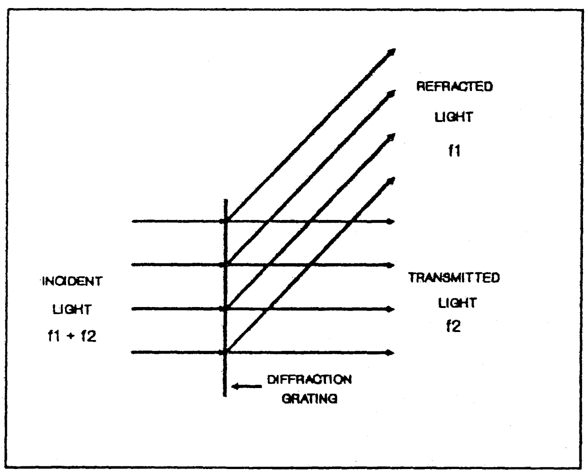
DICHROIC FILTER An optical device used in couplers that transmits all light frequencies above a certain cutoff frequency and reflects all lower frequencies. (See Figure 5-1.)

FIGURE 5-1
DICHROIC FILTER



DIFFRACTION GRATING An optical device used in couplers that bends light rays of different wavelengths into different angular paths, thus providing physical separation of the wavelengths. (See Figure 5-2.)

FIGURE 5-2
DIFFRACTION GRATING



DISPERSION The distortion (spreading) of a light pulse caused by light signals traveling at different speeds through an optical fiber because of mode or chromatic effects.

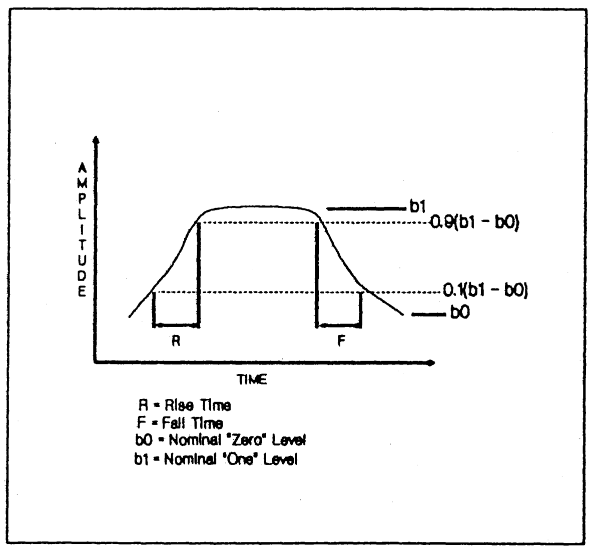
DISPERSION SHIFTED FIBER A single mode optical fiber whose dispersion characteristics are such that the wavelength at which dispersion is zero shifts from 1300 nanometers to 1550 nanometers. This allows a larger bandwidth of information to be transmitted farther without regeneration.

DYNAMIC RANGE The range of optical input levels in dB between the overload level and the minimum acceptable signal level for which a receiver will function without exceeding a specified Bit Error Rate.

F

FALL TIME The time required for an optical pulse to fall from 90 percent to 10 percent of its peak amplitude as measured from the nominal "one" level to the nominal "zero" level. (See Figure 5-3.)

FIGURE 5-3
RISE AND FALL TIMES



FIBER OPTIC LINK The combination of an optical transmitter, receiver, and optical fiber used to transmit information between two points.

FRESNEL REFLECTION Signal losses caused by reflections at the ends of fibers because of the differences in the refractive indices of glass and air.

FUSION SPLICING The permanent bonding of two optical fibers by welding their ends together, usually with a brief electric arc.

G

GIGAHERTZ One billion hertz (10^9).

GRADED INDEX FIBER An optical fiber whose core has an index of refraction that decreases parabolically radially outward from the optical axis toward the cladding. This fiber type provides a high bandwidth capacity and moderately high coupling efficiency.

I

INDEX MATCHING FLUID A substance whose index of refraction equals that of the fiber's core. Used to reduce Fresnel losses at the fiber ends in mechanically coupled fibers.

INDEX OF REFRACTION Also, Refractive Index. The ratio of the velocity of light in a vacuum to the velocity of light in a specified medium, e.g., glass.

INJECTION LASER DIODE (ILD) A semiconductor device in which lasing takes place within the P-N junction and the diode edge emits the light.

INTER-SYMBOL INTERFERENCE (ISI) The overlapping of an output pulse into the "no pulse" period or, as a worst case, into the next pulse period.

L

LASER Acronym for "Light Amplification by Stimulated Emission of Radiation." A device that emits nearly single wavelength continuously coherent light.

LIGHT EMITTING DIODE (LED) A semiconductor device that emits light of many wavelengths.

LIGHTWAVE Any electromagnetic radiation having a wavelength in the range from 800 to 1600 nanometers.

LINK LOSS BUDGET A mathematical study that itemizes all losses in a fiber optic link and includes margins and allowances for additional losses that may be introduced later. This study provides a systematic examination of transmission levels to ensure that the fiber and terminal equipment selected for use will provide satisfactory overall system performance.

LONG WAVELENGTH Refers to operation at wavelengths generally between 1200 and 1600 nanometers.

M

MACROBENDING LOSS Optical signal loss that occurs when the fiber bend radius decreases to the point that light rays within the core start to escape into the cladding. Long wavelengths are more susceptible to macrobending losses.

MATERIAL DISPERSION Unfaithful reproduction of the input pulse at the output (pulse spreading) because different wavelengths of light travel at different speeds through the optical fiber.

MECHANICAL SPLICE An optical fiber connection using fixtures or materials (connectors) rather than thermal fusion.

MERIDIONAL RAYS Light rays that intersect with the optical axis of an optical fiber.

MICROBENDING LOSS Optical signal loss caused by small, abrupt changes in the structure of the optical fiber core or sharp irregularities at the interface between the cladding and the core.

MODAL DISPERSION Unfaithful reproduction (pulse spreading) of the input pulse at the output caused by differential optical path lengths of the various modes in a multimode fiber.

MODE A single electromagnetic wave (oscillation) traveling in an optical fiber.

MODE FIELD DIAMETER (MFD) Defines the cross-sectional area available for efficient coupling of lightwave energy into and out of a single mode fiber. This diameter is somewhat larger than the core diameter.

MULTIMODE FIBER An optical fiber that supports propagation of more than one mode of light of a given wavelength.

N

NANOMETER One billionth of a meter (10^{-9}).

NUMERICAL APERTURE The measure of light acceptance of an optical fiber. The trigonometric sine of the maximum half angle (acceptance angle measured from the light ray to the optical axis) of light entering the end of a fiber such that the light will be propagated entirely within the core, i.e., total reflection. Normally only applies to multimode fibers. (See Figure 1-3.)

O

OPTICAL AXIS The axis of symmetry of an optical fiber; hence, the shortest transmission path through the fiber. (See Figure 1-3.)

OPTICAL DATA RATE The number of optical bits processed in a specific period of time, e.g., 45 megabits per second.

OPTICAL TIME DOMAIN REFLECTOMETER (OTDR) A test instrument used to locate faults in optical fibers by sending short pulses of light through the fiber and timing the arrival of backscattered signals caused by discontinuities in the fiber.

P

PARAXIAL RAYS Light rays that are nearly parallel with the optical axis.

PHOTODIODE A semiconductor device that converts light energy to electrical current.

PHOTON The smallest quantity of radiant electromagnetic energy.

PICOSECOND One trillionth of a second (10^{-12}).

PIGTAIL A short length of optical fiber permanently attached to a fiber optic device (source, detector, etc.) to which the transmission optical fiber can be connected.

PIN-FET Acronym for "Positive-Intrinsic-Negative - Field Effect Transistor." An FET added to a PIN photodiode to amplify the output electrical signal.

POSITIVE INTRINSIC NEGATIVE (PIN)

PHOTODIODE A semiconductor device consisting of a large intrinsic region (pure semiconductor material without P or N doping) located between P and N semiconductor regions. Photons absorbed in the intrinsic region create hole-electron pairs separated by an electric field, thus generating an electric current.

R

RAYLEIGH SCATTERING The change of direction of light rays caused by variations in the atomic or molecular structure of the optical fiber.

RECEIVER An optical-to-electrical converter consisting of a light detector and signal processing electronics.

RECEIVER SENSITIVITY A measure in dB of a detector's output current or voltage in relation to the optical input power. This characteristic is wavelength dependent.

REFLECTION An abrupt change in the direction of a light ray such that the ray remains in the originating medium when it strikes another medium with a different index of refraction, e.g., a light ray in the fiber core striking the cladding.

REFRACTIVE INDEX See Index of Refraction.

REGENERATOR A device consisting of a receiver and a transmitter that receives an attenuated lightwave signal and retransmits the signal with its original shape and increased power. Also called a repeater.

REPEATER See Regenerator.

RISE TIME The time required for an optical pulse to rise from 10 percent to 90 percent of its peak amplitude as measured from the nominal "zero" to the nominal "one" level. (See Figure 5-3.)

S

SHORT WAVELENGTH Generally wavelengths between 700 and 900 nanometers.

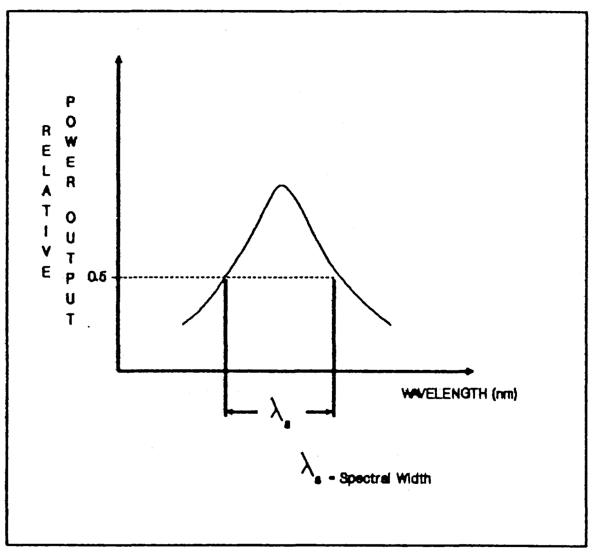
SINGLE MODE FIBER An optical fiber with a small core that supports only one propagation mode.

SONET Acronym for "Synchronous Optical Network." A proposed standard set of optical data rates and formats for optical interfaces that defines a synchronous optical hierarchy with sufficient flexibility to transport many different capacity signals.

SOURCE A device (LED, laser) that emits light to be transmitted in an optical fiber.

SPECTRAL WIDTH The width of a band of wavelengths emitted by a light source whose radiated power is not less than 50 percent of the maximum power in the band. (See Figure 5-4.)

FIGURE 5-4
SPECTRAL WIDTH



SPOT SIZE See Mode Field Diameter.

STEP INDEX FIBER An optical fiber whose index of refraction is uniform throughout its core.

SYSTEM GAIN The difference in dB between the power output level of the transmitter and the receive power level of the receiver in a fiber optic link.

T

TRANSDUCER A device that converts optical energy to electrical current and vice versa. See Transmitter and Receiver.

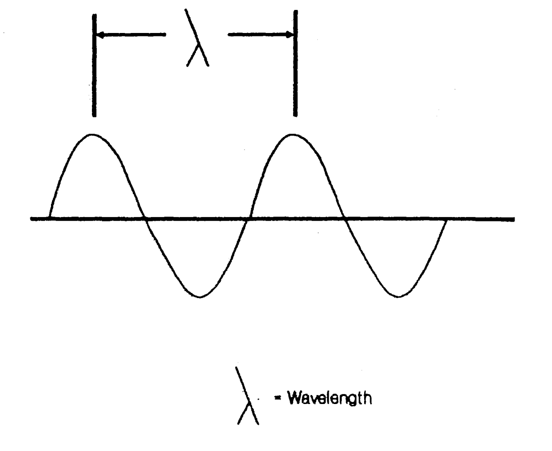
TRANSMITTER An electrical-to-optical converter consisting of a light source and driving electronics.

W

WAVEGUIDE DISPERSION
Electromagnetic signal distortion caused by the geometric properties of an optical fiber, e.g., propagation of light energy is at a slower speed through the cladding.

WAVELENGTH The speed of light divided by its frequency. Normally specified in micrometers or nanometers. Also the distance between equivalent points on consecutive cycles of the electromagnetic wave, e.g., the distance between crests. (See Figure 5-5.)

FIGURE 5-5
WAVELENGTH



WAVELENGTH DIVISION MULTIPLEXING (WDM) A method of simultaneously sending several signals through a fiber by using different wavelengths of light.

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