CHAPTER

19

System and Optical Networking Concepts

About This Chapter

The fiber-optic components described in earlier chapters are assembled into systems to provide communication services. This chapter takes a closer look at basic system concepts that were introduced in Chapter 3. To understand telecommunications systems and the emerging optical network, you need to learn both the specifics of how fiber-optic systems transmit signals and the tasks these systems perform. This chapter is the first of several that will teach you about optical networks and the services they provide.

An Evolving Network

The telecommunications industry is in transition. Signal transmission technology, services offered, and the structure of the industry are all changing. This book is about technology, so it concentrates on transmission and services, but business considerations also affect the choice of technology and the selection of services offered.

We'll start with a brief introduction to a few key concepts, then study system concepts in more detail.

Telecommunication Systems

Chapter 3 introduced the concept of telecommunication systems. Telecommunication networks deliver voice, video, and data services around the globe. Extensive interconnections among global, national, and local systems allow you to send electronic mail to Japan, to fax a document to Africa, or to phone someone in England.

The term *telecommunications* does not specify what technology delivers signals. Today's global network is a blend of three fundamental technologies. Electrical current

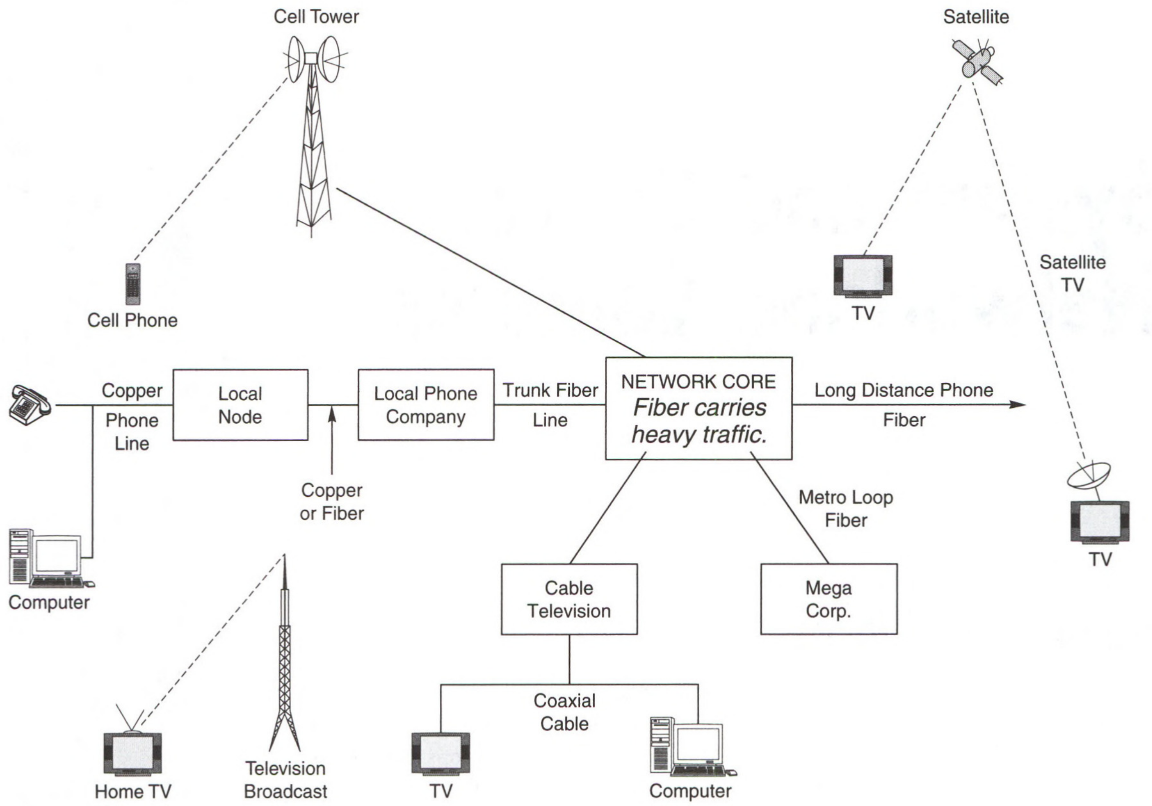


FIGURE 19.1
Technologies used for different types of telecommunications.

carries signals through copper wires, including both coaxial cables and the plain "twisted pair" used in telephone systems. Radio waves carry signals through air and space, between satellites, ground antennas, and mobile devices. Light waves convey signals through glass optical fibers.

Copper, wireless, and fiber play different roles in the global network.

These three technologies usually play different roles in the global network. In general, copper wires distribute signals to fixed devices, such as wired phones, television sets, and homes. Wireless (radio) signals travel to mobile devices, such as cell phones, laptops and pagers, and also broadcast video and audio programs to many points over wide areas. Fiber typically provides the superhighway, transmitting large volumes of information. Figure 19.1 shows the general layout.

This picture is a simplified one, and there are many cases in which the roles of these technologies overlap. For example, you may use a wireless network to link fixed computers in your house to avoid drilling holes in the wall. Signals often may be distributed partway over fiber and the rest of the way over copper. In some cases, optical fibers may run direct to people's homes. Satellites may provide some backbone transmission. But in general the categories of fixed distribution, mobile distribution, and backbone or "superhighway" transmission can be useful in understanding how networks operate.

Optical Networking

The term *optical networking* refers to networks in which signals are managed as well as transmitted in the form of light. This is a significant distinction. As you learned earlier, a network is built of "pipes" and "switches." Originally optical signals were transmitted only through pipes, and converted to electronic form by switches. The development of optical switches has made it possible to manage signals in optical form, without converting them to light.

Optical networking manages signals as light.

Optical networking so far has involved more marketing type than practical application technology. An *all-optical network*, in which signals remain in optical form out to the edges where they are converted into other forms, has theoretical advantages. However, true optical networking also has practical problems, so its applications have been limited.

Changing Business Models

Both telephone and cable television began as local monopolies that delivered only specific services, which regulators rigidly divided. Competition became the rule during the past two decades, first in long-distance telephone service, and later in local telephone service. Cable and phone companies, once rigidly separated, now compete head-to-head in Internet service. Cellular telephones are taking traffic away from "land lines." Many new companies emerged to offer a variety of services, and many of them fell, sometimes spectacularly, in the turbulent marketplace. Many survivors are now struggling to find ways to turn a steady profit.

The telecommunications business is undergoing rapid change.

As the business has changed, the global telecommunications network has grown and expanded, but many elements remain the same. The network still includes an inner core that processes signals and transmits them close to their destination, and an outer distribution network that collects signals from their origins, delivers them to the core, and picks them up as they emerge from the core and distributes them to their destinations. Phone service via the Internet is new, but a phone call is still fundamentally a phone call, even if it now can be routed over the Internet.

Telecommunication Network Structure

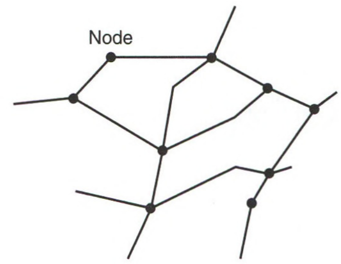
Today's global telecommunication network carries a mixture of voice, video, and data signals. Its structure is far more complex and fluid than in the days when it carried only long-distance telephone calls for national telephone monopolies. Let's look briefly at the overall topology before turning to the structural elements that build up the network.

Nodes and Connection Points

Telecommunication networks consist of links running between nodes, as shown in Figure 19.2. Typically there are multiple routes between pairs of nodes, both to handle traffic flow and provide backup in case of cable failures. The nodes direct signals to the next node, or distribute them locally.

Telecommunications networks are made of links between nodes.

FIGURE 19.2
Network connects nodes.



Each node is a point that serves many users—it could be a neighborhood distribution center, a telephone switching center in a small town, or a major switching center in a big city. These nodes, in turn, distribute signals farther to other nodes or to individual customers. Small nodes connect to larger ones and customers; larger nodes connect to smaller ones and to high-capacity *backbone systems.* The traffic is highest on the backbone routes between major population centers. Although individuals make more local calls, the signals are spread through many local cables, while long-distance calls are carried by a few high-capacity cables.

Types of Services

Telecommunications includes voice, video, and data signals.

We generally think of telecommunications as including voice, video, and data signals. Thanks to the Internet, digital data accounts for the largest share of traffic volume in the United States.

These services are distinct and have different transmission requirements. *Voice* requires little bandwidth per channel, but is highly sensitive to delays and requires two-way connections. Video requires much more capacity, and is also sensitive to delays, but its delivery requires only a one-way connection. Internet data comes in bursts, so transmission rates vary greatly with time, but the signal can tolerate delays.

Traditionally voice and video were transmitted on separate networks, each designed specifically for that type of traffic. Facsimile transmissions and computer data can travel over phone lines in the form of signals coded as a series of tones, but their speed is limited. High-speed Internet traffic is transmitted on dedicated lines using a protocol developed specifically for data. Dedicated networks are optimized for a specific type of traffic, but separate networks are expensive, so new techniques have been developed that convert signals into formats suitable for transmission on other networks. Voice signals can be converted for transmission on both cable television networks and the Internet, although Internet transmission uses a different type of switching, which imposes some limitations.

Circuit and Packet Switching

The telephone system is circuit-switched. The Internet is packet-switched.

The crucial operating difference between voice telephone transmission and the Internet is how signals are packaged.

Since the telephone was invented in the nineteenth century, voice calls have been made over dedicated circuits. Originally calls went over pairs of wires strung between phones;

now they are assigned a reserved slot in a stream of other data, called a *virtual circuit.* This reserved capacity means that once a connection is made, the phone responds the instant you start talking, and the person at the other end hears you immediately.

The Internet was designed around *packet switching*, which groups data together into packets for transmission. Each packet has an address header, which is read by network elements called *routers*, that direct the packet to its destination. Packets can fill the distribution pipeline much more efficiently because they don't have to reserve particular capacity, and they can be delayed. That's fine for electronic mail or for downloading pages from the Web, but annoying when it makes streaming video flow unevenly, or introduces delays into conversations over the Internet.

Circuit- and packet-switched signals are transmitted separately. Packet-switched signals can be repackaged for transmission over a circuit-switched network, and vice versa, but usually at added expense or with loss in quality. *Voice over Internet Protocol (VoIP)*, for example, converts voice signals for transmission on the Internet and is more efficient than ordinary phone lines, but does not provide the same guarantee of prompt signal delivery. You'll learn more about VoIP later.

Standards and Protocols

Telecommunications systems follow standards so that all parts of the network can understand each other. Standards codify a standard language or *protocol* for signal transmission. Industry groups establish most standards, and many companies produce products that adhere to such standards.

Standards define common languages for signal transmission.

Many different standards exist, but some are basic to system operation because they specify how bits are arranged for transmission. The *Internet Protocol (IP)* covers the arrangement of data packets for packet switching. *SONET, Asynchronous Transfer Mode (ATM)*, and the *Plesiochronous Digital Hierarchy* determine how data streams are interleaved to provide virtual circuits for circuit switching. You'll earn more about these standards in Chapter 20.

Transmission Topologies

In Chapter 3 you learned about the basic building blocks of telecommunications networks. Figure 19.3 shows four basic types of transmission that are important in fiber-optic systems. Let's look at each of these transmission topologies in more detail.

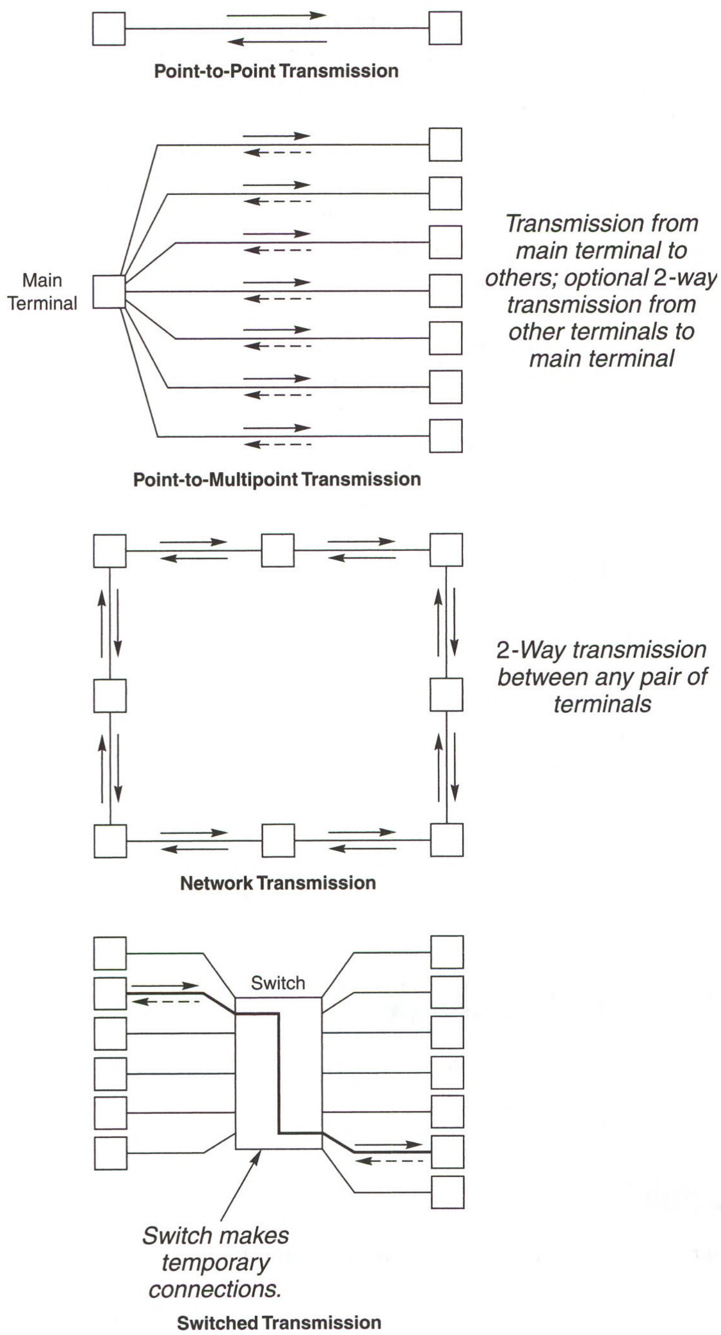
Point to Point

Point-to-point transmission provides two-way communication between a pair of terminals that are permanently linked together, with a transmitter and receiver on both ends.

Point-to-point transmission links pairs of terminals.

Conceptually, the distance between terminals doesn't matter. The two could be on opposite sides of the room or on opposite sides of the ocean. If the transmitter can't send signals through the entire length of fiber, optical amplifiers or repeaters can be added to boost signal strength. Examples of point-to-point links range from a cable linking a personal computer and a dedicated printer to a transatlantic submarine cable.

FIGURE 19.3
Types of transmission.



If you look closely enough, you can break other fiber-optic systems into point-to-point links. That reflects the reality that any fiber system has a transmitter on one end and a receiver on the other, although couplers in between may split the signals among multiple fibers.

Point to Multipoint (Broadcast)

Another family of systems sends the signal from one transmitter to many terminals. This is sometimes called *broadcasting* because it is analogous to the way a radio or television transmitter broadcasts signals through the air to many receivers. In a fiber-optic system, the terminals may or may not return signals to the central transmitter. If there is a return signal it is often at a lower speed than the broadcast transmission.

Point-to-multipoint transmission uses one transmitter to serve many terminals.

Because they serve many terminals, point-to-multipoint transmitters generally send higher-power signals than those in point-to-point systems. The basic design can vary considerably, as shown in Figure 19.4. A tree or star coupler can split the signal from one transmitter to drive

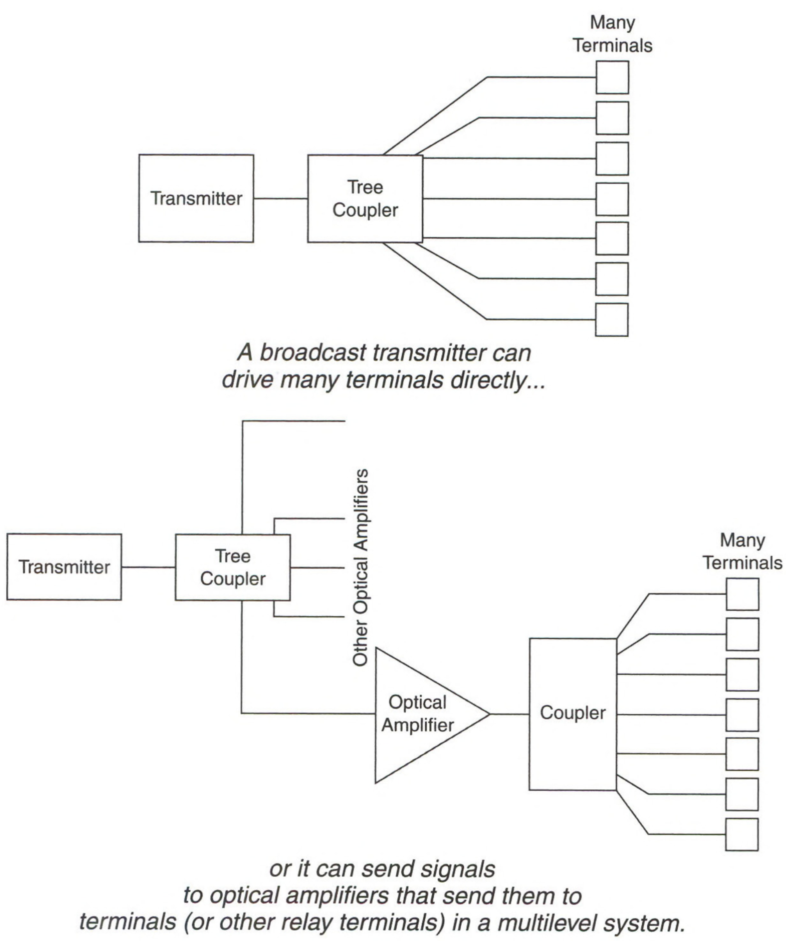


FIGURE 19.4
Point-to-multipoint transmission.

many terminals. Or the split signals can drive optical amplifiers that amplify the signal from the main transmitter and send it to terminals (or another stage of optical amplifiers).

Like a point-to-point fiber system, a point-to-multipoint fiber system makes quasi-permanent connections between transmitters and receivers. Typically, point-to-point systems include multiple levels of signal distribution. For example, the head end of a cable-television system sends signals to local distribution nodes, which in turn send signals to neighborhood nodes, which distribute signals to individual homes. Typically these systems send relatively few signals "upstream" from home terminals to the head end where signals originate. A *pure* point-to-multipoint system distributes identical signals to all terminals, but modern cable-television systems can distribute some unique signals to individual homes.

The main transmitter in a point-to-multipoint system is more "important" than the terminals it serves. Even in a two-way system, it sends most information handled by the system and is essentially an information provider (whatever you think of the offerings of your local cable system). Individual terminals provide little or no information, and they can link only to the main transmitter; they generally cannot communicate directly with each other. If the main transmitter fails, a point-to-multipoint system is off the air.

The most important point-to-multipoint fiber systems are cable television distribution networks. Most wireless networks, including cellular telephones as well as broadcast radio and television also use point-to-multipoint architecture. Functionally, however a broadcast television receiver is designed to decode all signals from transmitters in its area, while a cellular phone decodes only signals from the nearest available cell tower addressed to that phone.

Network Topology

Network topology directly interconnects many terminals.

The term *network* denotes interconnection, but it has a specific meaning when it refers to topology. *Network topology* is an arrangement of links that directly connects all terminals. Several variations of network topology are shown in Figure 19.5. All terminals can send and receive signals to or from any other terminal on the network. Small networks are often called *local-area networks.* Larger ones may be called *metropolitan-area networks* or *wide-area networks.*

Networks may link terminals in various configurations. Terminals may be arranged in a *ring*, with signals split from the ring and directed to their destination terminal, or passed directly through each terminal. Some ring networks are collections of point-to-point links that are regenerated at each terminal to overcome coupling losses. In *star* networks, signals travelling to and from each terminal pass through a central node, which may be either a passive coupler, which divides the input light, or an active coupler, which receives and re-transmits the signal.

A mesh network lacks a highly organized geometry.

An alternative is the *mesh* network, also shown in Figure 19.5, where interconnections do *not* organize terminals in a ring or star configuration, but instead form a mesh-like grid. In the example, each node has links to at least three other nodes. This creates multiple routes between nodes, a robust architecture.

As you can see, a mesh lacks a highly organized geometry. You can't just direct signals from one node to the next because typically there is no single *next* node. Switches or routers must be programmed where they should direct signals.

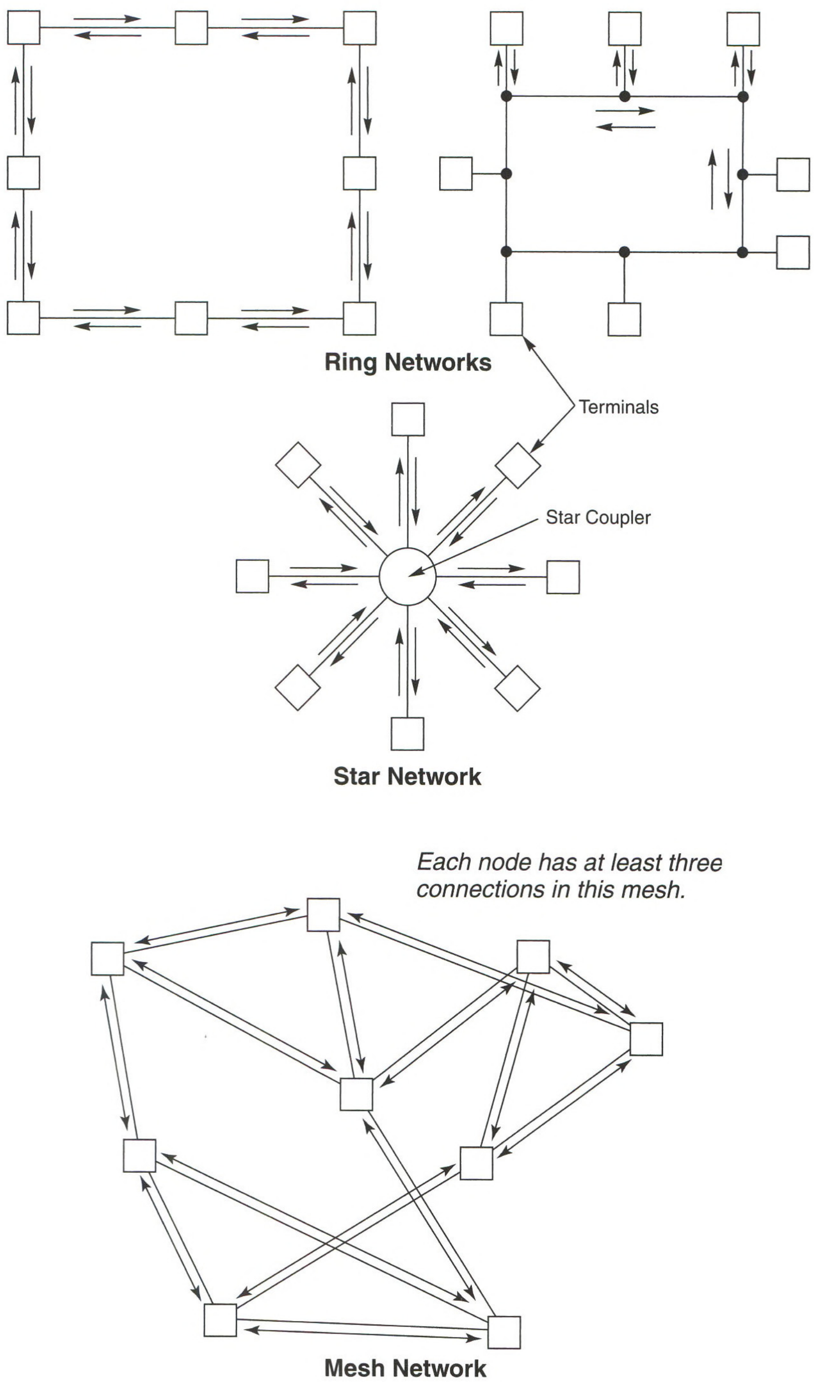


FIGURE 19.5 *Network transmission.*

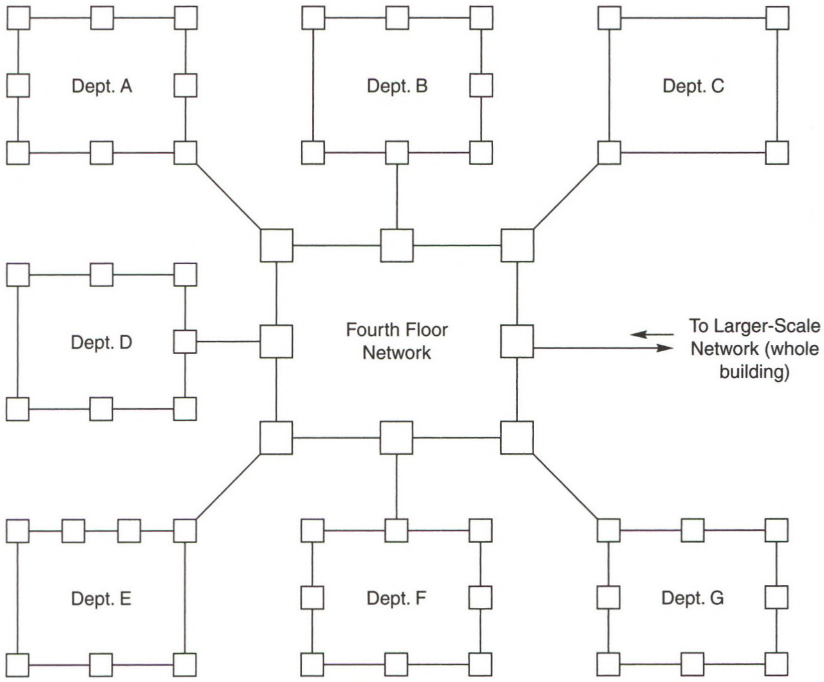


FIGURE 19.6
A network hierarchy, with small networks interconnected to make a large network.

Networks can be linked to make a network of networks.

Networks can be linked together with other networks to make a network of networks, as shown in Figure 19.6. In this example, each small-scale (department) network interfaces with a larger-scale (floor-wide) network, which in turn interfaces with an even larger (building-wide) network. Scaling this network-of-networks approach even further leads to the Internet.

As with point-to-point and point-to-multipoint systems, networks have permanent connections to each node and, except in mesh networks, the routing of signals can be changed only by rearranging cables. This means that the same terminals always talk to each other unless the configuration is changed. In practice, network connections usually go through patch panels with connectors that allow attaching and removing terminals. A typical example is a local-area network (LAN) for personal computers in an office. The terminals do not have to be identical, but do require a common protocol to talk with one another.

Switched Transmission

Switching allows temporary connections between pairs of terminals.

Adding switches to a communication network makes it more flexible. Switches allow any pair of terminals to send and receive signals directly to and from each other. The connections are inherently temporary, so each terminal can talk—at different times—to any other terminal, as shown in Figure 19.3. Depending on the system design, more than two terminals may be linked together at once. The telephone network is the standard example.

Switching increases system complexity, but adds tremendous power by making temporary connections to send signals between any pair of terminals linked to the switch. You can assemble switches in series, so each one directs signals at a different level. This allows the global telephone network to send calls around the world. To give a simplified example, one switch might direct a long-distance call to your state, another to the city where you live, a third to your part of town, a fourth to your block, and a fifth to your home. In practice, several of these switches may be in the same place—typically those serving your part of town, your block, and your home all are installed in the local telephone-company switching office.

Directing Signals

Point-to-point links direct signals to the desired destination because they connect only two points. Other transmission topologies require specific methods to direct signals to intended recipients. These methods vary considerably.

Broadcasting

Broadcasting is the simplest type of point-to-multipoint transmission. It simply sends the same signals to everybody. For example, everybody receives the same radio and television broadcasts if they have the proper antennas and receivers. Likewise, cable and satellite systems deliver the same television signals to all their customers, although premium channels require a special receiver that can decode the encrypted signals.

Broadcasting sends the same signals to everybody.

Wireless transmission broadcasts radio signals to all receivers in the area, so wireless services like cellular telephones require additional features that make them switched services.

Selective Reception

Point-to-multipoint transmission can function like point-to-point transmission if the receivers are selective. Selective receivers can't decode or are programmed to ignore any signals not directed to them.

Decades ago, party-line telephone service worked using a form of selective reception. Two homes would share the same phone line, which rang differently for each number. Residents were supposed to pick up the phone only when the call was to their number. Some services today use the same idea, as a distinctive ring that adds an extra number to an existing phone line.

Networks and cellular telephones require better security, called authentication, to assure that no one receives a call intended for someone else. Cellular signals can be encrypted so that only the phone to which the call is directed can decode them, although the radio waves reach other phones. The same can be done with local-area networks, so each terminal sees only the messages directed to it, although other messages may physically pass through the terminal. Authentication is handled by receiver electronics.

Authentication and encryption protect against eavesdropping.

Switching and Routing

Switching and routing are different operations.

Switching can take one of two different forms—*circuit switching* and *packet switching*. Circuit switching is used in the telephone network and performed by electronic or

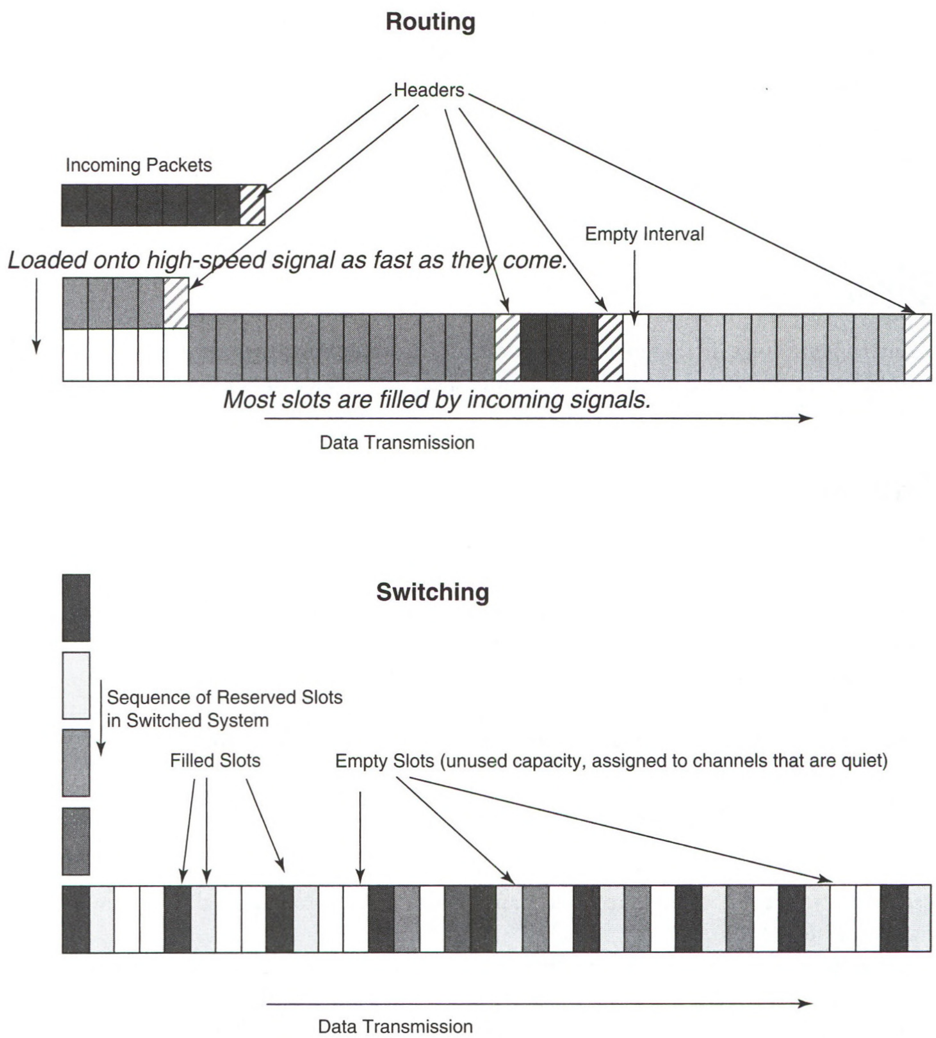


FIGURE 19.7
Routers use transmission capacity more effectively by packing signals closely together. Switches leave slots open because they reserve capacity.

mechanical devices that are confusingly called *switches.* Packet switching is used on the Internet and performed by hardware called *routers.* It's vital to remember that switches and routers are different types of devices, although they sometimes are mislabelled. To understand how they differ, let's look at each in more detail.

Switches are relatively simple electronic systems that create a temporary circuit linking two points. The connection process is controlled by information transmitted by the source when the circuit is set up—typically, when you dial a telephone number. Circuit-switched connections may be physical links through wires or optical fibers, or reserved bit slots in a high-speed digital signal that provide the equivalent capacity. As Figure 19.7 shows, the slots for each circuit switched signal are always available but may not be filled by data bits. Telephone switches create a temporary path for signals that guarantees the capacity of one voice circuit while both phones are off the hook, whether or not anyone is talking. Circuit switches work like the switches on a model train layout; once you set them, they automatically guide all signals to their destination.

Routers are more complex systems used for packet switching over a mesh network. At its source, the signal is broken down into one or more data packets, and each data packet is assigned a header that specifies the destination for the data. This can pack data bits together more efficiently, as shown in Figure 19.7. The router reads the header on each packet and determines the best route for each packet to follow, based on information including traffic conditions on the network. It then sends the packet to another router at a node closer to its destination. The next router repeats the process, sending the packet to another node, until the packet reaches the node that can direct it to the target terminal.

Routers direct packets by reading the attached headers.

Signal Formats

Signals can be transmitted through any medium in a variety of formats. The basic idea, as you learned in Chapter 3, is to modulate some property of a carrier with the signal to be transmitted. The transmission process is based on three key concepts: the carrier, modulation, and coding. Radio signals give a good example of these concepts.

A signal modulates a carrier wave.

Radio stations transmit at specific *carrier frequencies*, which are much higher than the frequency at which the transmitted signal varies. An oscillator at the station generates a continuous signal at the station's assigned carrier frequency; then the station modulates the carrier with the radio program being transmitted. For example, an FM station transmitting at 89.7 MHz has an oscillator that generates that frequency, and modulates that carrier with an audio signal, which is the program being broadcast. The broadcast signal is centered on the 89.7-MHz frequency, and your radio receivers tune into that frequency. The receiver electronically extracts the program and amplifies it, discarding the carrier. The coding of the signal determines how the receiver interprets it. Let's look at each of these steps.

Types of Modulation

The signal can modulate three properties of the carrier wave: its amplitude, frequency, and phase.

Amplitude modulation is the most common type of modulation in fiber optics, and is the simplest to understand. The amplitude of the carrier wave varies with the instantaneous strength of the signal being transmitted, as you saw earlier in Figure 10.5. For an AM radio station, when the program is loud, the amplitude is high, and when the program is quiet, the amplitude is low. The same type of variation occurs in fiber-optic transmission. An optical carrier wave, however, oscillates much faster than the signal varies, so the scale of Figure 10.5 is deceptive. If you were transmitting a 10-Gbit/s signal at a wavelength of 1537.4 nm (195 THz), the carrier wave would oscillate 19,500 times during the length of a single bit. Amplitude modulation can be viewed as multiplying the constant amplitude of the carrier by the time-varying amplitude of the transmitted signal.

Amplitude modulation is most common in fiber optics.

Frequency modulation is common in radio and television transmission, but unusual in fiber-optic transmission. Frequency modulation changes the carrier frequency instead of the carrier amplitude. In radio transmission, frequency modulation is easy to implement electronically and effectively filters out random static. However, frequency modulation is rarely used in fiber-optic transmission because it's much harder to implement and background noise is much lower. Frequency modulation has been used in experimental fiber-optic systems, where it's sometimes called *coherent transmission*. Digital frequency modulation is known as *frequency-shift keying*.

Phase-shift modulation varies the phase of transmitted waves in proportion to the instantaneous strength of the signal. In principle, a receiver can decode the phase-shift signal by combining the shifted input with an identical carrier wave generated at the receiver. Phase-shift modulation is more practical than frequency modulation in fiber-optic systems, but so far it's been used only in high-speed transmission demonstrations. Digital phase-shift modulation is known as *phase-shift keying*.

Analog Signal Coding

Signal coding is the form in which the transmitted information is represented. Analog signals are replicas of the original rather than coding; digital signals, however, require special coding, which also can enhance system performance by detecting and correcting transmission errors.

Analog signals replicate the original.

An analog signal is an exact electronic replica (or analog) of the input. For example, if the input signal is a 1000-Hz sound wave, the analog is a 1000-Hz electronic signal. An analog signal varies continuously with the instantaneous strength of the input. Amplitude modulation illustrates this most clearly, and Figure 10.5 shows how carrier-wave amplitude varies with the amplitude of the input signal. Analog transmission has long been standard for FM radio and television, although digital transmission is beginning to replace analog broadcasts. Cable television systems are the only place where analog transmission is widely used in fiber optics.

Digital Signal Coding

So far we've considered digital transmission to be simply a series of 1 and 0 bits, but it's not always that simple in practice. The signal level may be coded in various ways to optimize transmission.

NRZ coding is used in most fiber-optic systems.

The simplest approach is to send a high signal level for a 1 bit and a low signal level for a 0 bit, as shown at the top of Figure 19.8. This is called *NRZ* or *no return to zero coding* because the signal level does not change between bits if the value of the second bit is the same as the first. Thus the signal level stays high throughout a series of 1 bits and only drops to the low level to transmit a 0 bit. NRZ coding is used in most fiber-optic systems, but has performance problems at high transmission speeds. Long strings of identical bits keep the transmitter operating at the same level, making it easy for the receiver to lose the clock signal, causing transmission errors.

Several alternative approaches change the signal level more often to better preserve clock transmission. These schemes are more elaborate, but may be required at high transmission speeds. The most important of these is *return to zero (RZ) coding*. The signal level during the first half of a bit interval is low for a 0 bit and high for a 1 bit. In both cases, the signal level returns to 0 for the last half of the bit interval, as shown in Figure 19.8. This assures more transitions, making it easier to retain clock signals at high speeds, although there still are no transitions during series of 0 bits.

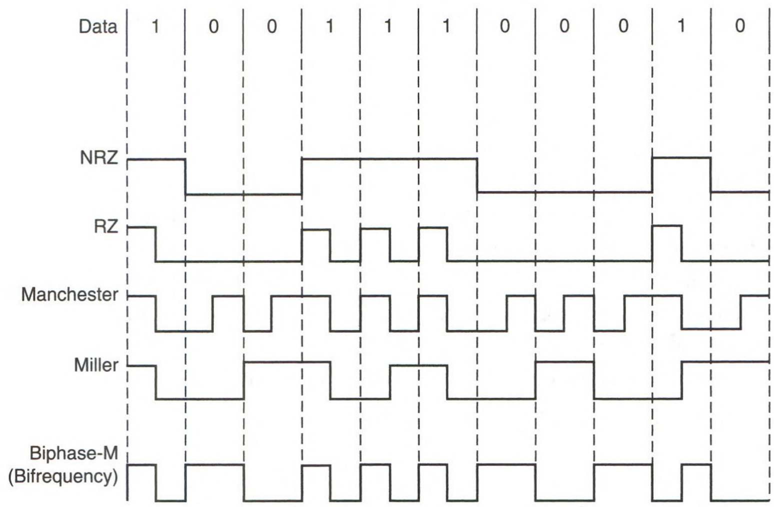


FIGURE 19.8
Digital data codes.

Other digital coding schemes further increase the number of level transitions. These include:

- *Manchester coding*—Signal level always changes in the middle of a bit interval. For a 0 bit, the signal starts out low and changes to high. For a 1 bit, the signal starts out high and changes to low. This means that the signal level changes at the end of a bit interval only when two successive bits are identical (e.g., between two 0s).
- *Miller coding*—For a 1 bit, the signal changes in the middle of a bit interval but not at the beginning or end. For a 0 bit, the signal level remains constant through a bit interval, changing at the end of it if followed by another 0 but not if it is followed by a 1.
- *Biphase-M or bifrequency coding*—For a 0 bit, the signal level changes at the start of an interval. For a 1 bit, the signal level changes at the start and at the middle of a bit interval.

Each type of coding has its own advantages and disadvantages. NRZ coding is simple to implement, and requires no more than one transition per bit, easing bandwidth requirements. However, long intervals of 0s or 1s can produce a steady signal level, making it easy to lose clock timing. RZ coding has more transitions during "on" bits, but can produce long intervals of 0 signal during a sequence of 0s. Codes that always have transitions during bits, such as Manchester and biphase coding, require higher bandwidth but generate their own clock signal to aid in timing. Other types of digital coding also are possible, but the details fall outside the scope of this book.

Error Correction

A different kind of digital coding, often called *forward error correction*, adds extra bits to the original signal in order to detect and correct errors. These techniques evolved from simple error-detecting schemes for computer data that added parity bits to the sequence of stored bits. Forward error correction greatly reduces transmission errors, allowing designers to stretch system margin. Instead of adding an optical amplifier, a more powerful transmitter, or a more sensitive receiver, the designer can add forward error correction circuits in the transmitter and decoding circuits in the receiver.

Error-correction codes operate on blocks of data.

Error-correction codes operate on a block of data. Their power depends on both the mathematical code used and the number of bits added. All codes have limited capacity, and can be overwhelmed by large numbers of errors. Their overall effect is to reduce the bit error rate, so an otherwise limited system can give acceptable performance.

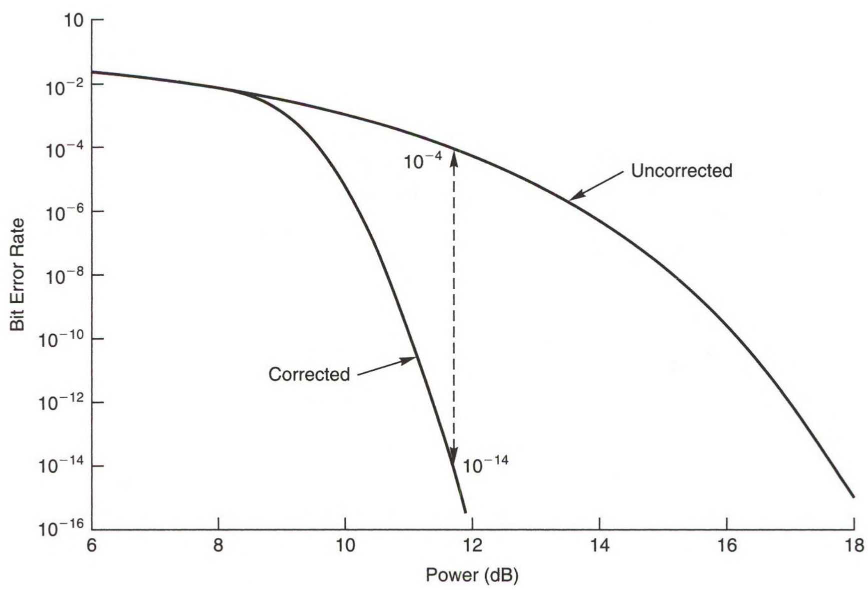
Error detection is simpler than correction, and can be done simply by adding one extra bit to each eight-bit byte of data in computer storage. This extra bit, called a *parity bit*, is calculated by the system so the sum of the digits is always either an odd or an even number. If the sum gives the wrong parity, the computer flags an error. Addition of a second bit to each byte, with proper coding, allows correction as well as detection of one bit error. This simple coding is relatively inefficient, but information theorists have devised much more efficient ones.

Error correction requires extra bits, but improves bit error rate.

Codes are usually identified by a pair of numbers (n, k), where n is the total number of bits in the block and k is the number of data bits. (The numbers may also refer to bytes in a block.) Adding $n - k$ bits imposes an overhead, additional bits that have to be transmitted in order to carry the nominal data rate. The smaller the number of added bits $(n - k)$, the more efficient the code. Efficiency is measured by the overhead ratio, $(n - k)/k$, and generally increases with the size of the coded blocks. Blocks of hundreds or thousands of bits can overhead from 7% to 25%.

Many codes are possible, although only a few are in practical use. One important type is *Reed-Solomon codes,* which group m-bit symbols into blocks containing $2^m - 1$ symbols or $m(2^m - 1)$ bits. Thus 8-bit bytes are grouped into 255-byte blocks. The code can correct errors in up to half the number of added bytes, so a (255, 239) Reed-Solomon code with 16 check bytes can correct up to 8 errors in 239 data bytes and has 6.3% overhead. It can reduce bit error rate from a raw 10^{-4} to a corrected rate of 10^{-15}, as shown in Figure 19.9. A (255, 223) code has about 13% overhead but can correct up to 16 byte errors, and enhances performance even more. Both codes have been adopted as standards for fiber-optic transmission.

FIGURE 19.9
Raw and corrected bit error rate with a Reed-Solomon (255, 239) code.



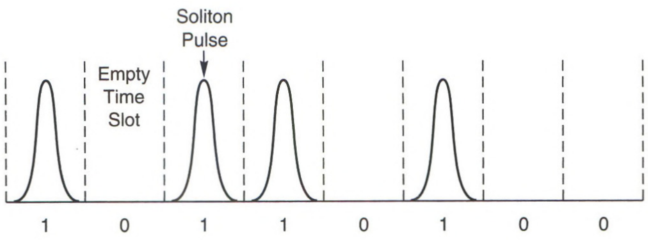


FIGURE 19.10
Soliton pulses modulated with a digital signal.

Soliton Transmission

Soliton transmission has unusual properties that deserve additional explanation. *Solitons* are a special type of return-to-zero pulse coding based on pulses that rise and fall in a specific pattern, which allows them to regenerate their shape as they travel along a fiber. The transmitter generates a series of solitons, some of which are switched off by an external modulator, producing a train of pulses as shown in Figure 19.10.

Solitons retain their shape as they travel through a fiber.

Solitons strike a delicate balance between two effects that tend to degrade normal pulse transmission. Chromatic dispersion stretches out pulses carrying a range of wavelengths, while self-phase modulation spreads out the range of wavelengths. For pulses of the proper shape, the two types of stretching offset each other, keeping the pulse shape unchanged as it travels through the fiber. The mathematics of soliton transmission are complex, but the physics were first observed in waves of water seen on canals in the nineteenth century.

Soliton pulses suffer attenuation, but optical amplifiers can compensate for the loss. Their nature enables them to retain their original shape, canceling out distortion. In fact, the input pulses don't have to be perfect solitons because they adapt their shape as they pass through the fiber. In practice, interactions between soliton pulses traveling in the same fiber at different wavelengths complicate transmission. Nonetheless, solitons continue to be developed for high-speed, long-distance transmission.

Transmission Capacity

Transmission capacity is a key figure of merit, which measures the amount of information a communication system can carry. In fiber-optic systems it usually is specified for a single fiber. Two-way communication usually requires a pair of fibers, one to carry signals in each direction. (In some cases a single fiber carries signals simultaneously in both directions.) Capacity may also be given for an entire cable, particularly for submarine cables. Total cable capacity is the sum of the capacities of all the fiber pairs.

Transmission capacity is the amount of information a fiber can carry.

The usual measurement of capacity for analog systems is the bandwidth in megahertz or gigahertz. For digital transmission, capacity is measured in *megabits, gigabits,* or *terabits per second*—that is, how fast the system can transmit bits.

Capacity is increased by multiplexing, the combination of many signals into one. As you learned in Chapter 3, you can multiplex electronic signals in time or frequency, and multiplex optical signals by wavelength. Let's take a closer look at each of these approaches, and see how they combine to determine capacity.

Electronic and Time-Division Multiplexing

Electronic multiplexers combine two or more signals to produce a signal that drives a fiber-optic transmitter.

Time-division multiplexers generate a single bit stream.

Electronic multiplexing began long before optical fibers were first used in telecommunications. Electronic equipment combines two or more separate input signals into a single output signal. That combined signal is transmitted through a communication system and then "demultiplexed" to break it into its original components. Multiplexing takes different forms in digital and analog systems.

Digital systems use time-division multiplexing (TDM), which combines several input signals into a single bit stream, as shown in Figure 19.11. In the example shown, four separate 1.5-Mbit/s inputs feed into a multiplexer. The multiplexer combines the signals, selecting first one pulse from input 1, then a pulse from input 2, and so on, in sequence. Essentially, the multiplexer shuffles the pulses together and retimes them because the lower-speed pulses are too long to stuff into a faster stream of bits. At the other end of the system, a demultiplexer sorts the bits out, putting bit 1 into channel 1, bit 2 into channel 2, and so forth. Interleaving also can be done byte by byte or in larger chunks.

Time-division multiplexing can shuffle incoming data bits together so perfectly because all the input data signals must arrive at the same rate. That is, you can only make a 6 Mbit/s output signal by interleaving four 1.5 Mbit/s data streams. A time-division multiplexer could not combine signals at 3, 2, and 1 Mbit/s to yield one 6 Mbit/s data stream, although the total input and output rates match. You would need to combine those signals in some other way.

As you will learn in Chapter 20, time-division multiplexing works with a fixed *hierarchy* of data rates. Several signals at one rate are merged to make one signal at a higher rate, and several signals at that rate are merged to make one at an even faster rate. This is an inherent limitation of time-division multiplexing, but not all fast digital signals are assembled in this way.

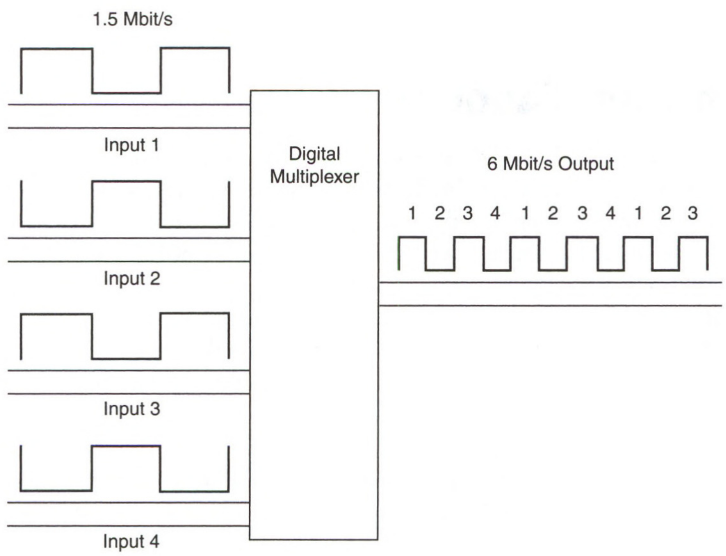


FIGURE 19.11
Time-division multiplexing combines digital signals.

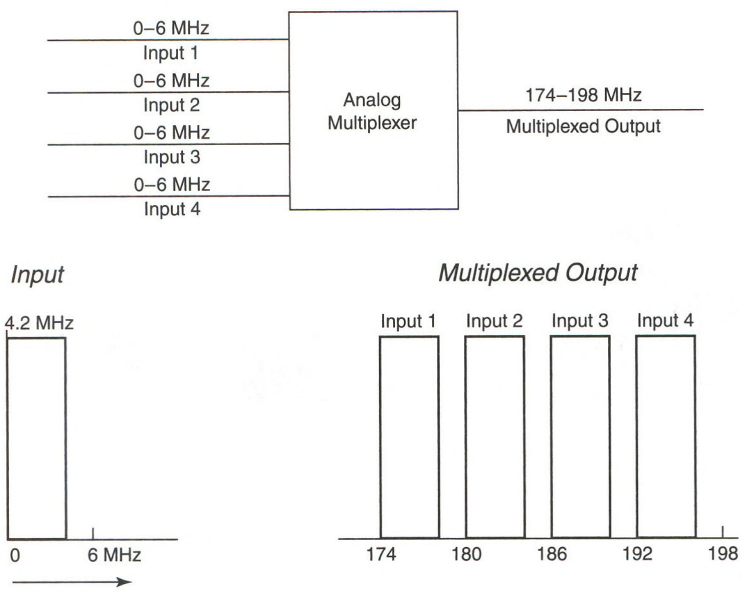


FIGURE 19.12 *Analog frequency-division multiplexing for cable television.*

Analog multiplexing works differently, by modulating carrier signals at separate frequencies with separate analog input signals. This is often called *frequency-division multiplexing* because it multiplexes by assigning each input signal to its own carrier frequency. Radio stations share the broadcast spectrum in this way, each transmitting at a different frequency to avoid interfering with each other. In an analog cable-television system, each video channel is assigned to a separate carrier frequency.

Analog multiplexing modulates multiple carrier frequencies.

Figure 19.12 shows a simplified example of frequency-division multiplexing in a small part of a cable transmission band. Each analog input signal has a video bandwidth of 4.2 MHz, with the audio carried at a slightly higher frequency. Each channel is assigned a bandwidth of 6 MHz, the standard for analog video, but the figure uses only a narrower 4.2 MHz band to show the separation of the channels. In this example, the first signal modulates a carrier to produce signals at 174–180 MHz, the second modulates a carrier at 180–186 MHz, the third a carrier at 186–192 MHz, and the fourth a carrier at 192–198 MHz. This generates a composite signal of 174–198 MHz at the transmitter. At the receiver, bandpass filters pick out the original channels. (Broadcast radio and television leave empty slots between adjacent channels in the same area to prevent interference, but this is not necessary in cable systems.)

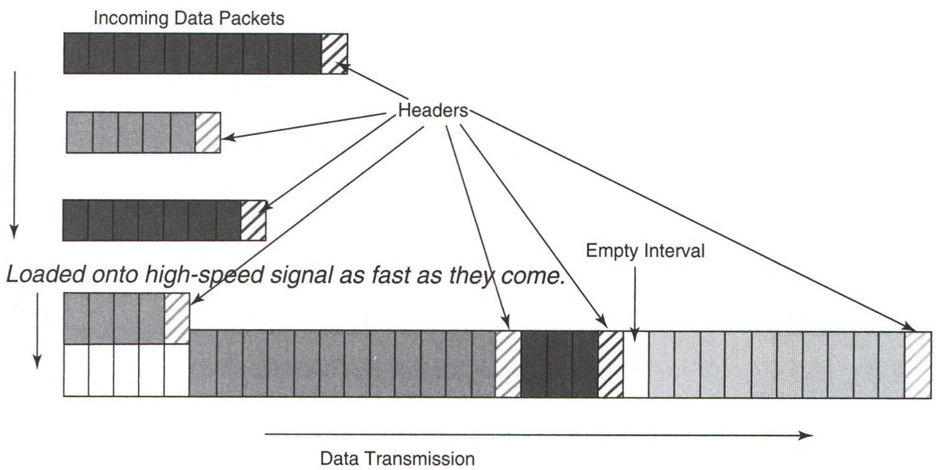
Both analog and digital electronic multiplexers generate composite signals at the combined bandwidth or data rate. Digital signals can be further multiplexed to higher data rates, but this is rarely done for analog signals. The maximum data rate for a single channel depends on the transmitter, receiver, and fiber capacity.

Multiplexing in Packet Switching

High-speed signals can be generated directly, without TDM.

You don't need to interleave input data streams by time-division multiplexing to generate a high-speed digital signal. You can build up high-speed digital signals by assembling them

FIGURE 19.13
High-speed signal assembled from data packets.



directly from data bundled in packets, as shown in Figure 19.13. The packets do not have to arrive at a particular rate or contain a particular number of bits, although they must have headers that specify their destination. Figure 19.7 compares this to TDM circuit switching.

The data rate is set by the clock speed of the transmitter, which generates a specified number of pulses per second. Data packets are lined up for transmission in the sequence of their arrival. The transmitter sends one packet at a time, starting with the header, which contains address information, and proceeds through the rest of the bits in sequence. If another packet is waiting, the transmitter starts sending it; otherwise it sends blank intervals.

It's like lining people up to get onto a moving staircase where each step holds one person. The people line up at the base, and one gets onto each passing step. As long as people are in line, every step is filled. Steps only go empty if no one is left in line. To make the analogy better, you could imagine tour groups lining up, with a single leader acting as the "header" of each group.

Statistical multiplexing combines multiple packet streams that may have different data rates.

Multiple packet streams are combined by a technique called *statistical multiplexing*, rather than by interleaving bits. Incoming data packets on each channel accumulate in separate storage buffers. The multiplexer takes packets from each buffer in turn, keeping track of the traffic on each channel, then allocates more time to the busiest channels.

Statistical multiplexing is used for transmitting Internet Protocol (IP) traffic. Like time-division multiplexing, it combines data streams from multiple sources into a single faster signal. However, it does not require a rigid hierarchy of incoming data rates. Because statistical multiplexers average bursty traffic over many channels, the total capacity of the input channels may be higher than their output capacity. That is, a statistical multiplexer might have 10 inputs delivering up to 100 Mbit/s, but one output able to transmit only 600 Mbit/s. That design can work as long as the average input is below the peak capacity. For example, if each input channel averages only 20 Mbit/s, the combined inputs should be safely below 600 Mbit/s most of the time. (This sort of averaging is common in telephone networks, which don't have output connections for every input line because most lines are used only a small fraction of the time. Problems only arise when everyone makes long-distance calls on Mother's Day.)

Statistical multiplexing requires a set of priorities because too many packets may queue up while waiting to be transmitted. One approach is to allow packets to "time out" after a certain interval, like a person who gives up after waiting on hold for customer service. This method is used in the traditional version of the Internet Protocol (IPv4). A refinement is to set higher priority for delay-sensitive traffic, such as telephone conversations or streaming video, so it goes to the head of the transmission queue, while lower-priority data packets wait; this is used in IPv6, which is not yet implemented across the entire Internet.

Wavelength-Division Multiplexing

Wavelength-division multiplexing (WDM) is the transmission of different signals on multiple wavelengths through the same fiber. It closely resembles electronic frequency-division multiplexing, but is done at the much higher frequencies of light waves, as shown in Figure 19.14. The optical channels at 193.1, 193.2, 193.3, and 193.4 THz are the optical counterparts of the radio-frequency channels at 174, 180, 186, and 192 MHz shown in Figure 19.13.

WDM transmits signals at multiple wavelengths through one fiber.

Channel spacing may be defined in terms of frequency or wavelength, but if the carriers are in the optical or infrared part of the spectrum, the process is generally called wavelength-division multiplexing. Standards have been set for two types: *dense-WDM (DWDM)* and *coarse-WDM (CWDM).*

Dense-WDM packs signals closely together, usually for long-distance transmission, and usually in the *erbium-amplifier band* between about 1530 and 1610 nm. Standards specify DWDM spacings in frequency units as 50, 100, and 200 GHz, which correspond to about 0.4, 0.8, and 1.6 nm in wavelength units near 1550 nm. The same standards also allow for spacing at 400 and 1000 GHz, which usually are not considered DWDM. The packing density of DWDM systems is limited by the modulation bandwidth of the signals, so 2.5-Gbit/s signals can be packed more tightly together than can 10-Gbit/s signals.

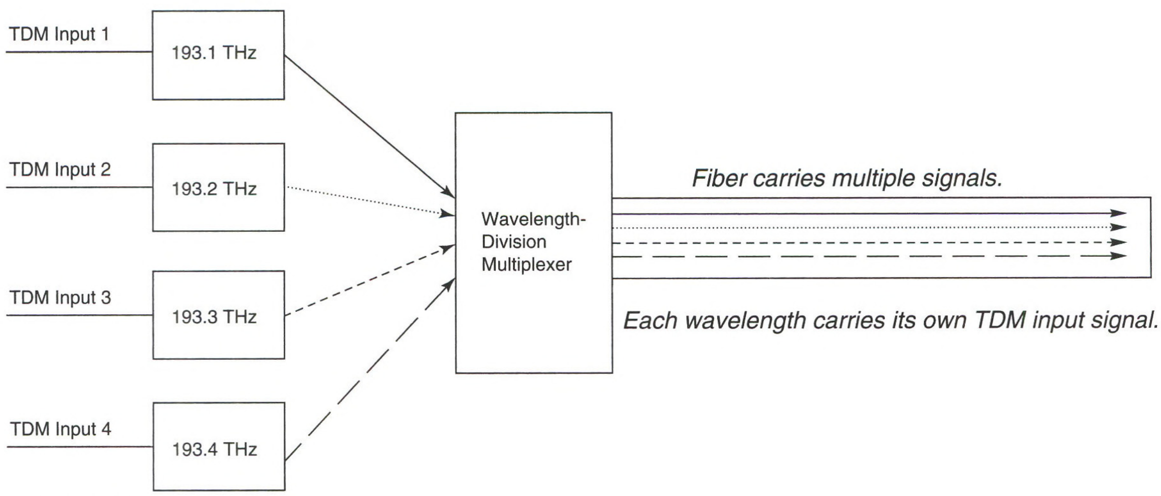


FIGURE 19.14
Wavelength-division multiplexing.

Coarse-WDM is used in metro networks, which don't require amplification.

Coarse-WDM spaces channels more loosely to reduce equipment costs. Current specifications space 18 channels at 20-nm intervals between 1270 and 1610 nm. The primary applications of coarse-WDM are in metro networks, which can carry heavy traffic but don't require optical amplification.

Total fiber capacity is limited by the range over which WDM is possible. In practice, amplifier bandwidth limits the range in amplified systems. The range is larger in unamplified systems, where the limits come from fiber attenuation. Potential capacities can reach staggering levels. The entire erbium band can accommodate more than 100 channels at 10 Gbit/s, allowing commercial systems to offer total capacity of more than 1 Tbit/s. Experimental systems have transmitted more than 10 Tbit/s a few hundred kilometers through a single fiber.

Most WDM systems have few populated channels.

Today's DWDM systems generally populate only a few optical channels because actual transmission requirements fall far short of total fiber capacity. However, carriers reserve the extra channel capacity for inexpensive future expansion.

Signal Management and Optical Networking

Multiplexing is involved in signal management.

Multiplexing is closely related to the management of signals transmitted through a telecommunications network. Multiplexing combines signals so they can be transmitted through fiber or other media. Multiplexed signals may be demultiplexed or otherwise broken up when they have to be switched, redirected, or otherwise managed. Electronically multiplexed signals are broken up into their component bit streams (or analog channels). WDM signals are broken up into their component wavelengths.

Much publicized during the telecommunications bubble, optical networking is signal management in the optical domain based on wavelength. An important advantage of optical networking is that WDM channels are entirely independent of each other, unlike TDM signals that must be in the same family of formats. A single fiber can carry several wavelengths, each transmitting in different formats. One wavelength can carry Gigabit Ethernet, another a 2.5-Gbit/s stream of Internet data, a third a single digitized high-definition video signal, and a fourth an analog cable-television signal. All you need are transmitters, receivers, fibers, optical amplifiers, and WDM optics that can handle the required data rates.

Signal management in the optical domain also requires *optical switches* that can select one or more optical channels in a WDM system. Ideally, optical networks also should be able to convert signals from one wavelength to another for transmission in other parts of the network.

Granularity measures how finely a signal can be broken up into its component parts.

The ability to switch individual optical channels can aid signal management by easing access to individual data streams. Suppose 40 streams of 2.5-Gbit/s data are multiplexed in a single fiber. Optical networking could easily isolate one data stream if the signals were 40 WDM optical channels. Isolating one data stream from a 100-Gbit/s TDM signal is much harder. The ease of breaking up multiplexed signals into their components is called *granularity*. The more granular the signal, the better carriers can meet customer needs and the more efficiently they can manage their networks.

Optical networking is still evolving, and it is too early to predict its final shape. Issues to be resolved include the technologies for wavelength conversion and other functions, what services should be offered, and what customers require.

Transmission Distance

The telecommunications network is global in extent, but transmission distance remains an important element of system performance. Two types of transmission span are important in fiber optics—the distance between individual optical amplifiers, and the distance between regenerators or repeaters, which are separated by a series of amplifiers.

The span between a pair of amplifiers is limited by the input power and the fiber loss. When signal power diminishes to an unacceptable level, you need an amplifier. Amplifiers aren't needed in short systems, where the required power reaches the receiver without amplification.

The end-to-end distance is limited by the degradation the signal experiences as it passes through a series of amplifiers. Once noise and dispersion have degraded the signal sufficiently, it must be regenerated. Typically regenerators are built into terminal nodes of a system, so the space between regeneration points is the length of a system, such as that of a submarine cable link from New York to London, or a terrestrial cable from Chicago to Saint Louis.

Signal degradation limits end-to-end distance.

As you will learn, trade-offs are involved in the two distances. Increasing the spacing between amplifiers also increases the noise added to the signal and reduces the end-to-end distance. That's why repeaters have to be spaced much closer together in cables that cross the Atlantic ocean than in cables that run a few hundred kilometers between large cities.

Cost and Reliability

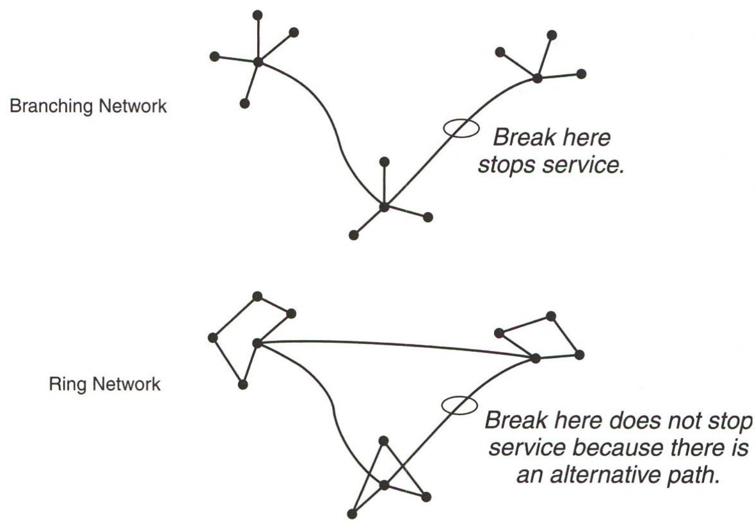
Network cost and reliability are critical concerns for carriers that provide telecommunication services. A cutting-edge system that sets transmission speed records is fine in the laboratory, but no carrier will want to install it if it is out of service half the time or requires a small army of top-level engineers to maintain.

Costs fall into two broad categories: *capital expense (capex)* and *operating expense (opex)*. Capital expense is the cost of buying new equipment. Operating expense is the cost of running the network, including power, normal maintenance, required adjustments, and repairs. Often they are charged to separate departments, but choices are made based on trade-offs between the two. For example, an optical add-drop multiplexer that can be reconfigured from a central facility will incur more capital expense than one that requires manual adjustment. But the manually operated model will have higher operating expense because technicians have to travel to the site to make adjustments. Engineers decide between the two types of systems based on their expectations of operating requirements. Typically spending an extra \$50,000 on the latest, greatest, automated system isn't reasonable if the system is only 50 miles from the control center and will require only one adjustment every year. But it's another matter if the site is 500 miles from the control center and requires adjustment twice a week.

Costs are divided into capital expense and operating expense.

Construction and installation costs typically count as capital expense and are another important factor. Normally carriers plan capacity for future expansion, so their network designs include spare fibers and extra wavelength slots in fibers to provide that capacity. Adding an extra pair of fibers to a cable being installed now is much cheaper than installing an additional cable later.

FIGURE 19.15
Branch and ring topologies for connecting network nodes.



Ring and mesh networks can better withstand cable failures than branching networks.

Reliability depends on factors such as network topology and operating environment as well as the choice of equipment. Traditional networks branched out from a few central points, as shown in Figure 19.15. This reduced cable and installation costs, but left the network vulnerable to interruption by a single cable break. Modern systems that carry heavy traffic are arranged in rings or meshes, so an alternative path remains between any two points in the network if a cable breaks.

The operating environment also is important for reliability. Much equipment is outdoors, where it must withstand moisture and extreme temperatures. Remote optics and electronics are installed in shielded cases, or "repeater huts," which provide some protection. Sensitive equipment usually is installed in temperature-controlled office-like environments.

What Have You Learned?

1. The global telecommunications network is evolving rapidly in response to changes in business and technology.
2. The network includes copper, wireless (radio), and fiber links.
3. Optical networking manages light signals, usually in the heart of the network.
4. Telecommunications networks are made of links between nodes. They carry voice, video, and data signals, which have different transmission requirements.
5. The telephone system is circuit-switched. The Internet is packet-switched.
6. Standards or protocols allow different equipment to exchange signals in a common format.
7. Point-to-point transmission links pairs of terminals permanently. Point-to-point multipoint or broadcast transmission sends signals from one transmitter to many terminals.
8. Networks link many terminals with each other in various configurations.

9. Packet switching uses routers to deliver signals in a network; the routers read data headers on the packets to determine their destination. The Internet uses packet switching.
10. Circuit switching establishes temporary connections between pairs of terminals; it is used for telephone systems.
11. A signal modulates a carrier wave at a higher frequency. It may modulate amplitude, frequency, or phase of the carrier. Amplitude modulation is most common in fiber optics.
12. No return to zero (NRZ) coding is the most common way to code digital signals for fiber-optic transmission. Signals in NRZ form do not return to zero after a 1 bit is transmitted.
13. Error-correction codes operate on blocks of data, correcting errors that arise in transmission. The number of corrections depends on the coding scheme.
14. Transmission capacity is the bandwidth or data rate of a communication system.
15. Time-division multiplexing interleaves data in several incoming bit streams to generate a composite bit stream containing all the data. All input is at the same rate, and the output rate is a multiple of the input rate.
16. Statistical multiplexing combines multiple streams of data packets, which may arrive at different rates, to generate a single stream of data packets. It is used on the Internet.
17. Wavelength-division multiplexing and frequency-division multiplexing combine signals at different wavelengths or frequencies. WDM applies to optical transmission through a fiber; FDM applies to radio or microwave transmission through air or coaxial cable.
18. Most WDM systems have few populated channels.
19. Granularity measures how finely signals can be broken up into their component parts. It is important for signal management.
20. Transmission distance may be measured as spacing between amplifiers or regenerators. Amplifier spacing depends on power and attenuation; regenerator spacing depends on noise and dispersion.
21. Costs are divided into capital expense and operating expense.

What's Next?

In Chapter 20, you will learn about the standards developed for fiber-optic systems.

Further Reading

Roger L. Freeman, *Fundamentals of Telecommunications* (Wiley InterScience, 1999)

Gary M. Miller, *Modern Electronic Communications,* 6th ed. (Prentice Hall, 1999)

Jean Walrand and Pravin Varaiya, *High-Performance Computer Networks,* 2nd ed. (Morgan Kaufmann, 2000)

Questions to Think About

1. Internet routers read headers on data packets, and use that information to direct the packets toward the proper destination. What type of network architecture would you expect to be used to connect routers in the Internet backbone? Why?
2. Can you use headers to control the flow of data packets around a ring network in which signals pass through all the terminals anyway?
3. An electronic time-division multiplexer generates signals at 1 Gbit/s. If it has eight inputs, what are their data rates?
4. How would an optical time-division multiplexer work?
5. How is wavelength-division multiplexing analogous to frequency-division multiplexing?
6. What are the prime limitations on amplifier spacing and regenerator spacing? How do the two affect each other?

Chapter Quiz

1. What type of telecommunications is packet-switched?
   a. cable television
   b. standard telephones
   c. the Internet
   d. all
   e. none
2. What type of telecommunications is circuit-switched?
   a. cable television
   b. standard telephones
   c. the Internet
   d. all
   e. none
3. What protocol covers the arrangement of data for packet switching?
   a. the Internet Protocol
   b. SONET
   c. Asynchronous Transfer Mode
   d. Plesiochronous Digital Hierarchy
   e. NRZ coding
4. A router does which of the following?
   a. It makes circuit-switched connections between terminals.
   b. It broadcasts signals to many points.
   c. It optically directs light signals to their destinations.

d. It reads packet headers and directs signals to their destinations.
e. It is equivalent to a switch.

5. A switch does which of the following?
a. It makes circuit-switched connections among terminals.
b. It broadcasts signals to many points.
c. It converts packet headers to circuit-switching directions.
d. It reads packet headers and directs signals to their destinations.
e. It is equivalent to a router.

6. Amplitude modulation is used for
a. digital transmission of a single 2.5-Gbit/s optical channel over fiber.
b. analog transmission of cable-television signals.
c. AM radio broadcasting.
d. optical transmission of Internet data.
e. all of the above

7. What is the proper name for digital coding in which a strong signal means a 1 and a low or zero signal means a 0?
a. no return to zero (NRZ)
b. return to zero (RZ)
c. Manchester coding
d. frequency-division multiplexing
e. phase modulation

8. Interleaving incoming bit streams to produce a faster output signal is called
a. packet switching.
b. frequency-division multiplexing.
c. time-division multiplexing.
d. statistical multiplexing.
e. wavelength-division multiplexing.

9. Simultaneously transmitting separate signals through an optical fiber at different wavelengths is called
a. packet switching.
b. frequency-division multiplexing.
c. time-division multiplexing.
d. statistical multiplexing.
e. wavelength-division multiplexing.

10. What type of multiplexing requires all incoming signals to be at the same data rate?
a. packet switching
b. frequency-division multiplexing
c. time-division multiplexing

d. statistical multiplexing

e. wavelength-division multiplexing

11. Transmission capacity of an optical fiber is the

a. total amount of information the fiber can transmit.

b. distance between amplifiers.

c. number of wavelengths the fiber can transmit, regardless of data rate.

d. distance from end to end.

e. data rate that can be transmitted at 1550 nm.

12. A fiber-optic system can transmit 2.5 Gbit/s on each of 40 optical channels, with an amplifier spacing of 100 km. The company that operates the system has installed transmitters and receivers at only 4 wavelengths. What is the data rate of the installed system?

a. 2.5 Gbit/s

b. 10 Gbit/s

c. 40 Gbit/s

d. 100 Gbit/s