Cables from homes run directly to the switching office or to an intermediate node. At nodes, individual phone lines may be multiplexed together to generate a single digital signal for transmission from the node to the switching office over fiber or over copper. Typically homes near the switching office are served directly from there, but homes farther away—particularly clustered in new developments—may be served from a local node or concentrator that distributes signals from a remote point.

The small businesses in the business district receive their service through a local distribution node. The insurance office needs the capacity of a T1 line but most other businesses, like the shoe-repair shop, need only one or two ordinary phone lines. The Town Hall has its own T1 line direct from the central office. The biggest business in our little town has its own T3 fiber-optic connection to the switching office.

All these services are processed through the central office. If the town manager calls the shoe repair shop to see if her shoes are finished, the call goes through the central office, where a switch connects one of the town phone lines to another phone line going to the shoe shop. If someone wants to call overseas, the switching office directs the call to the long-distance network, which makes the overseas connection. Incoming calls from the regional phone network go through the switching office, which makes the connections needed to direct them to the proper destination.

Telephone switching offices do not have one outgoing line for every customer because normally all phone lines are not in use simultaneously. Telephone companies decide how many output lines to allocate to a switch, based on statistical averages of usage.

"Access" Customers

All local traffic does not have to pass through a traditional switching office.

Changes in the telecommunications network mean that local traffic need not pass through a traditional telephone switching office. Figure 25.1 showed a number of other organizations on the edge of the network, such as large corporations and universities. These organizations could have their own internal switches and be hooked directly to a metro network, as seen in Figure 24.3. Their telephone traffic could go directly to long-distance carriers, to regional carriers, or over lines that they leased from regional carriers for corporate use. For example, a state university might have leased lines from administration offices in the state capitol to campuses around the state.

Internet Service Providers are also on the edge of the network. Instead of sending circuit-switched signals to telephone switches, they generate packet-switched signals, which are routed over the Internet Protocol network. As you learned in Chapter 23, some Internet traffic winds up on leased phone lines.

Large organizations typically generate both Internet and telephone traffic, which they may transmit over metro networks to their Internet and telephone connections.

Other Carriers

Cell phone and competitive phone companies have their own switching offices.

Back in the days of telephone monopolies, every community had one central office, operated by *the* telephone company. In urban and suburban parts of the United States, that was generally AT&T, but in small towns it was often a small local company that served just that community and maintained links to AT&T's regional network.

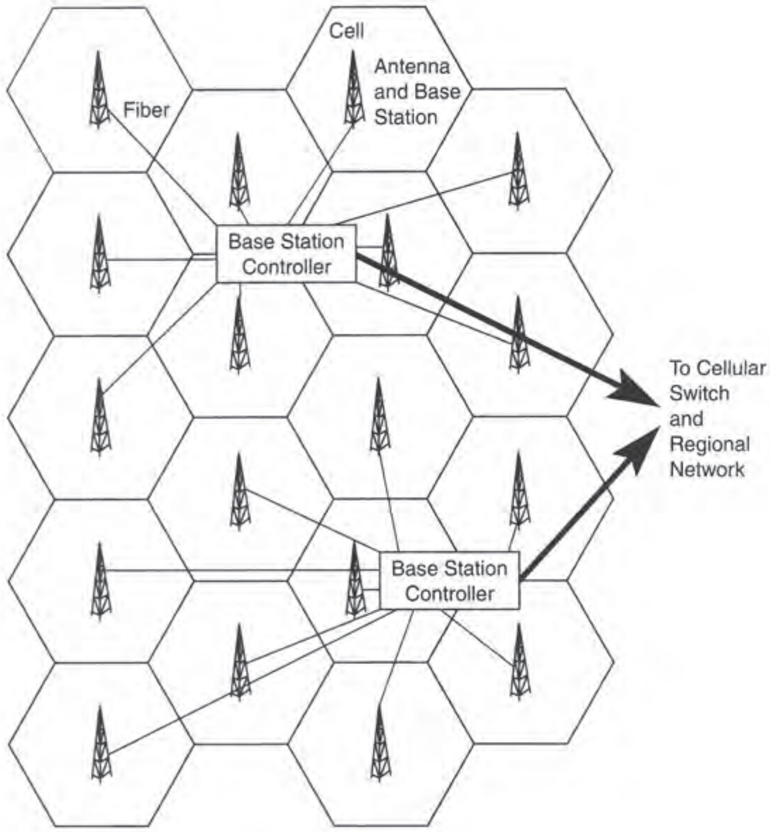


FIGURE 25.3
Cell-phone network.

Two trends have changed that pattern: the spread of mobile or cellular telephones, and the introduction of competition into the local fixed telephone network.

Cellular or mobile phones connect to the telephone network using radio waves. The service area is divided into cells, as shown in Figure 25.3, each with an antenna and a base station that serve phones located within the cell's area. As a user moves across the service area, the call is handed off from cell to cell. The antennas and base stations function like distribution nodes in a wire-line phone system, receiving signals from the switch and relaying them to individual phones. Cables carry the signals from the base transceiver back to a base station controller, which links to the switching office that serves the cellular phone network.

Because this book is about fiber optics, we won't look closely at the cellular network. However, the cellular network isn't always divided up into the neat hexagons shown in Figure 25.3. Terrain, buildings, vegetation, and changes in weather can affect transmission.

CLECs compete with incumbent wire-line phone companies.

Telecommunications regulations encouraged development of *competitive local exchange carriers* (CLECs), which provide local telephone service over cables. Many CLECs folded when the telecommunications bubble collapsed, but four basic types remain:

- Companies that lease space on the dominant phone company's network of cables, paying a rate set by regulators. The cables they lease connect to the competitive carrier's telephone switches, which make the required connections in the area and around the world.

- Facilities-based competitive carriers, which build networks of cables that overlay an area served by the dominant telephone carrier. Few of these companies exist today.
- Cable television companies that offer telephone service over their coaxial cable networks (see Chapter 27).
- Voice over Internet Protocol (VoIP) systems, which digitize voice signals at homes or offices and transmit the resulting data signals over the Internet or over digital lines using Internet Protocol. Many cable television systems use this technology.

The rest of this chapter concentrates on standard local wire-line telephone networks. You will learn more about VoIP systems later. Chapter 27 covers voice service on cable networks.

Distribution, Concentrators, and the Subscriber Loop

Cables distribute signals from the central office to subscribers.

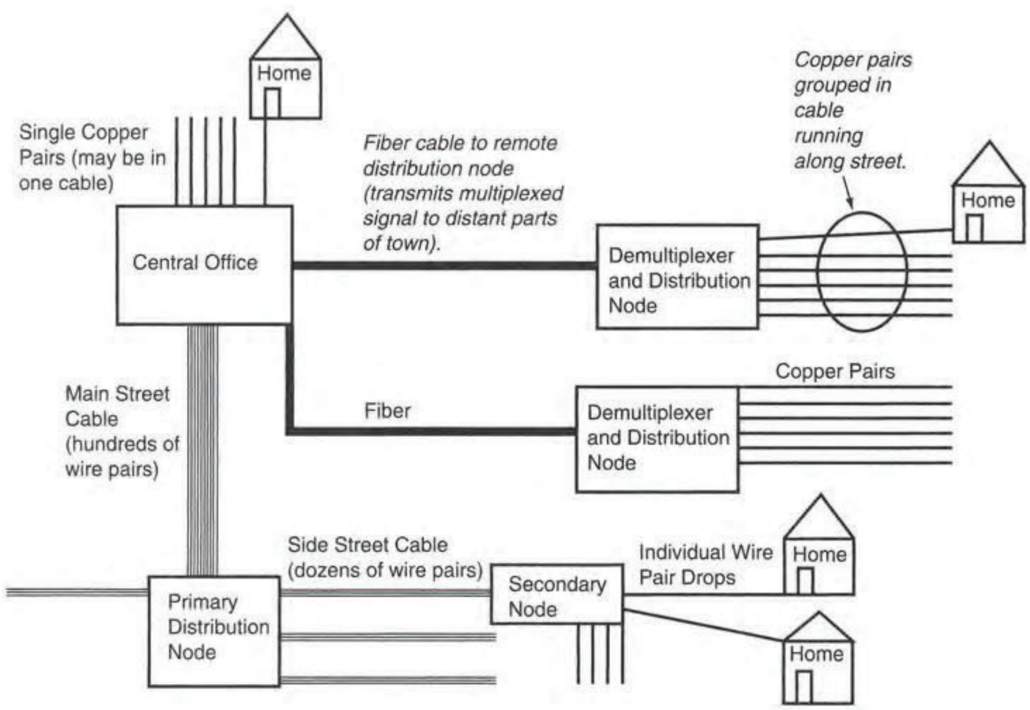
Twisted pairs of copper wires connect to telephones.

A network of cables distributes signals from the central office to subscribers. The structure of this network varies from place to place.

Figure 25.4 shows a typical network structure. Homes near the switching office are served by copper wire pairs running directly to the switch, as shown at top. Thick cables with hundreds of wire pairs run along main streets to service boxes or manholes, where the cables are split into smaller cables with dozens of wire pairs, as shown at bottom left. The smaller cables run down side streets and distribute service to individual homes. The wires running from these cables to homes are called *drops*.

The copper wiring used in these cables, called *twisted pairs*, traditionally is a pair of wires twisted together to reduce the noise they pick up from other sources. Flat ribbon cables

FIGURE 25.4
Subscriber loop distribution.



with two or four lines are used over short distances, such as in household telephone wiring, but long runs of untwisted wiring can act as antennas and pick up noise like radio signals. Each wire pair carries traffic for a single telephone circuit or phone line.

Distant homes are served by multiplexing signals at the central office and sending the multiplexed signals through fiber-optic cables to remote distribution nodes, as shown at the right in Figure 25.4. Although the scale of the figure doesn't show it, typically these fiber cables run a few miles. Copper cables run from the remote distribution node to homes, with fat cables subdividing into smaller cables with lower wire counts on side streets, as shown near the central office in the figure.

Copper wires can carry voice telephone signals several miles without serious degradation. However, the maximum transmission distance is shorter for other services, particularly Digital Subscriber Line (DSL), which I will cover later in this chapter. That has led to some refinements in design of subscriber loops.

Copper wires can carry voice, but not DSL, for several miles.

In the 1980s and early 1990s, telephone companies installed systems called *digital loop carriers* that multiplexed together many voice channels and distributed them at remote locations, as shown at the right of Figure 25.4. This seemed like a good idea at the time, because a single fiber transmitting at the modest 6.3 Mbit/s T2 rate could carry 96 telephone circuits. The fiber cables were much smaller, cheaper, and sturdier than copper cables with equivalent capacity. A single 12-fiber cable could easily carry 500 phone lines at 6.3 Mbit/s per fiber, so these systems were installed to new developments or during upgrading of existing phone systems.

However, old digital loop carriers posed a problem when telephone companies started thinking about DSL. Digital loop carriers transmit only the voice frequencies carried by phone lines, but DSL relies on transmitting higher frequencies that are lost in multiplexing. Thus the old digital loop carriers can't deliver DSL to phone lines they serve. It's hardly the only case where yesterday's bright idea becomes tomorrow's bottleneck.

To get around this bottleneck, telephone carriers must install modern fiber systems that transmit signals differently. Data to be delivered over DSL can be separated from digitized voice signals at the central office, then multiplexed in separate data streams. At the remote demultiplexing node, the two signals can be combined into an analog voice/DSL line, as they would be at the central office if the DSL subscriber were closer. The important difference is that the modern systems can move more functions of the switching office to the remote node; the older systems can only multiplex voice signals.

Business subscribers are served the same way as home telephone subscribers. The larger the business, the bigger the information pipelines needed to serve them. You can see this if you look back to Figure 25.2. The smaller businesses like the shoe-repair shop need just a phone line or two. Businesses that need more phone lines or high-speed Internet access may lease blocks of lines from the phone company. The insurance office and town hall both have T1 lines. The "pretty big business" has a 45-Mbit/s T3 line. The higher-capacity services may be delivered partly or entirely over fiber. A T3 fiber-optic cable runs from the switching office to the node serving the business district, and a short copper cable delivers T1 service from that node to the insurance company.

The structure of the local phone network is changing as technology develops, companies offer new services, and subscribers respond to the new technology and services. We will return to these evolving trends later, after describing conventional and emerging services.

Subscriber and Access Services

Traditional phone lines were designed to carry only analog voice signals.

The traditional subscriber loop was designed to carry voice telephone signals, called *Plain Old Telephone Service* or *POTS* in the industry. The local telephone network now provides many other services. When facsimile machines came into use, it was much easier to add them to the existing telephone network than to build a separate fax network. All you did was install a new phone line, plug in the fax machine, and tell people to send faxes to the new phone number. Likewise, dial-up modems take advantage of existing phone networks between your home or office and your Internet Service Provider instead of requiring a complete new network. Digital Subscriber Line technology expands on this trend by enhancing the transmission capacity of voice phone lines.

A broader range of services is offered to business and access customers, whose demand has steadily grown from multiple voice phone lines to large numbers of phone lines and high-speed data links. We'll look briefly at the most important services.

Leased Lines

Businesses lease phone lines for high-volume service.

Telecommunication users who need a large volume of service often *lease lines*, renting transmission capacity in bulk from a carrier. When dealing with telephone companies, they generally lease bulk capacity in a standard telephone-industry format, such as a T1 or T3 line, or an OC-3 carrier. The lines may run between user facilities, such as between buildings used by a large company or between a city's data-processing center and city hall. They also may run from the user's facility to another point, such as between a university and a regional Internet node or a long-distance carrier.

Although the service is called a *leased line*, the signals may not be carried over a physically separate wire, fiber, or cable along the entire route. If a company leases a T3 line between a downtown office building and a suburban factory, it is buying a guaranteed capacity of 45 Mbit/s on that route. The telephone company may time-division multiplex that 45-Mbit/s signal into a 2.5-Gbit/s OC-48 signal that a fiber transmits from downtown to the suburban central office, then run a separate fiber pair to the plant. The user sees no difference between that service and a separate pair of fibers—but the phone company can lease the capacity more cheaply.

Access lines generally serve the same purpose, but may be arranged differently. For example, the company may rent one optical channel on a fiber in a metro network that runs from downtown to near its suburban plant. The carrier may transport the signal in OC-1 or OC-3 form through the fiber, using its own equipment. Alternatively, the company could supply its own transmission equipment and send the signal in whatever form it wanted. If the line is intended to link the local-area networks in the factory and company headquarters, the signal might be in Gigabit Ethernet form.

Access lines also can go beyond the region. If a large magazine publisher has offices in Boston and Chicago, it might lease an OC-12 circuit between the two cities so it can transmit signals at up to 622 Mbit/s. The publisher might also lease OC-3 lines between both magazine offices and its printer in Mississippi. The company's signals can be combined with other signals and multiplexed to higher speeds for part of the route, but the user would not see any difference. Alternatively, users could lease wavelengths or dark fibers and have all the capacity they could use for themselves between two points.

Telephone Lines

Traditional phone lines carry analog signals at 300 to 3000 Hz for voice telephony. This isn't high fidelity, but it's adequate for intelligible speech. The bandwidth is limited by the attenuation of copper wire pairs, which increases with frequency and distance. Over short distances, copper wires can have surprisingly high bandwidths, so suitable copper cables can carry 1 Gbit/s on the desktop, but telephone companies long ignored these capabilities.

Fax machines and dial-up modems encode digital data as audio tones.

Fax machines and dial-up modems encode digital data as audio tones in the 300 to 3000 Hz audio range transmitted by analog phone lines. These signals must be clear and strong enough to survive conversion to digital format for regional and long-distance transmission. Standard level 3 fax signals can transmit up to 14,400 bits per second, and dial-up modems have nominal data rates to 56,000 bits per second, although in practice they are limited to about 53,000 bits/s.

The traditional telephone system converts these analog signals to digital form at the switching office or an intermediate node between the subscriber and the switch. Newer services transmit signals in digital format direct from the subscriber.

The original digital telephone service was *Integrated Services Digital Network (ISDN)*, transmitting 144 kbit/s over twisted wire pairs. As envisioned in the 1980s, that capacity would be divided between two 64-kbit/s digitized voice lines and one 16-kbit/s data line. More recent versions dedicate all the transmission capacity to digital data. However, ISDN required expensive special telephone equipment, phone companies were very slow to offer it, and few customers wanted it, especially in the United States. The service is still available in some locations, but is often called IDSL so that it sounds similar to DSL, although the two use different technologies.

DIGITAL SUBSCRIBER LINE (DSL)

Digital Subscriber Line (DSL) transmits digital data over copper wires at frequencies higher than those used for analog voice transmission. Ideally, DSL signals can be transmitted over the same twisted-pair lines used for voice conversations, with a standard phone responding only to the voice signals and the DSL modem responding only to the data. In practice, it often isn't that simple, and may require a device, called a *splitter*, that separates the low analog voice frequencies from the higher frequencies carrying the digital data.

DSL transmits data on phone lines at frequencies above the normal voice range.

There are several versions of DSL. The data rates they can transmit depend on the quality of the phone lines and the length of wire separating the subscriber from the switching office, as well as on the design. Load coils used to improve the quality of analog voice transmission also attenuate the high frequencies that carry DSL signals, so they can't be used with DSL. Some phone lines can't carry high frequencies well enough. Even in the best phone lines, attenuation increases with frequency, so the data rate possible decreases with transmission distance, as shown in Figure 25.5 for two types of DSL.

Table 25.1 lists several DSL-related technologies and their nominal data rates and maximum transmission distances. The actual data rate achieved at the maximum distance typically is well below the maximum rate, unless noted. The limiting distance is measured along the cable route, which is not a straight line, so many homes fall outside the limit even

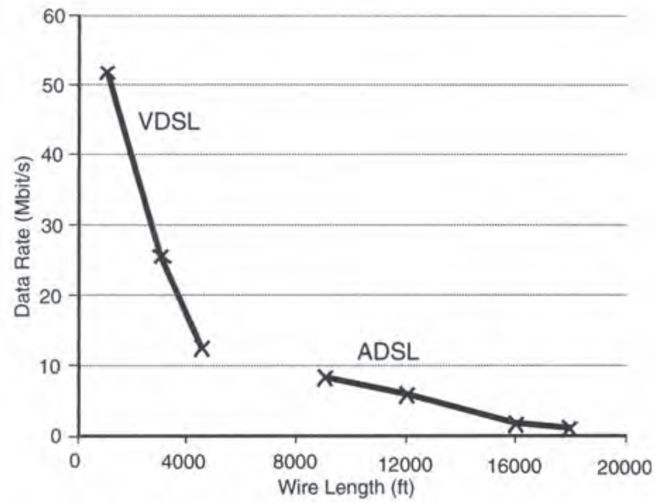


FIGURE 25.5
DSL data rates vs. wire length.

in cities or inner suburbs. Because data rate decreases with distance, it generally is impossible to achieve the maximum speed over the maximum possible distance. For example, the *Asymmetric Digital Subscriber Line* (ADSL) format is rated to send 8.448 Mbit/s to a terminal 9000 ft (2.7 km) away, but only 1.5 Mbit/s to a terminal at 18,000 ft (5.5 km).

As Table 25.1 shows, higher-speed DSL formats, notably VDSL, can't carry signals far. That's an intentional design choice; VDSL is intended for use in areas where a short length of copper runs between a home and a fiber-optic node. That trade-off is inevitable because of the bandwidth limitations of copper.

DSL rates depend on length and quality of lines and marketing decisions.

Different sources may quote different maximum data rates for DSL services, and some subscribers may not be able to receive DSL service at all. This reflects wide differences in the quality and length of phone lines, evolution of the technology, and marketing decisions by companies offering DSL services. Some phone lines are not suitable for DSL. Twisted pair attenuation is higher on the high end of the DSL spectrum, so long lines can't handle DSL signals. The nominal limit used to be 18,000 feet, but has been edging higher. Other phone lines may have incompatible equipment attached, or may not meet quality requirements. The reasons aren't always obvious. For unknown reasons, my phone company says two of its three phone lines into my home are suitable for DSL, but the third is not.

After some early problems, DSL has become popular for broadband Internet connections. DSL lags behind cable modems in the United States, but is more common in most other countries.

Emerging Services and Competing Technologies

In telecommunications some technologies that are "just around the corner" stay that way for a long time before quietly evaporating. One example is the video-telephone, which started as the stuff of pulp science fiction in the 1920s (see Figure 25.6). AT&T introduced the first

Table 25.1 Types of digital subscriber line services

Technology	Standards	Nominal Data Rate	Specified Maximum Distance
ISDN	ANSI/ITU	128 or 144 kbit/s both ways	18,000 ft (5.5 km) (longer distances possible)
G.Lite ("Splitterless" DSL)	ITU	1.5 Mbit/s downstream, 384 kbit/s upstream	18,000 ft (5.5 km)
ADSL (Asymmetric Digital Subscriber Line)	ANSI	8 Mbit/s 640 kbit/s downstream, upstream	9,000 ft (2.7 km) (at 8 Mbit/s)
ADSL	ANSI	1.5 Mbit/s downstream	18,000 ft (5.5 km) (at 1.5 Mbit/s)
SHDSL (Symmetric High-rate DSL)	ITU 6.991	2.3 Mbit/s both ways on one pair 192 kbit/s both ways	10,000 ft (3 km) (at 2.3 Mbit/s) 20,000 ft (6 km) (at 192 kbit/s)
T1	Digital Telephone Hierarchy	1.5 Mbit/s both ways	3,000 ft (900 m)
RADSL (Rate Adaptive DSL)	—	Adaptive— to 9 Mbit/s downstream, 1 Mbit/s upstream	12,000 ft (3.6 km)
VDSL (Very high DSL)	ANSI	13 to 52 Mbit/s down, 1.5 to 2.3 Mbit/s upstream	4,500 ft (1.4 km) at 13 Mbit/s; 1000 ft (300 m) at 52 Mbit/s

commercial video-telephone service, called *Picturephone,* in 1970, but it quietly faded away. Today webcams are cheap additions to personal computers, and their pictures appear on thousands of Web sites, but few people bother using them for videoconferencing.

Nonetheless, telecommunications is changing rapidly, so now we'll look at future trends both in the network and in the services it offers.

FIGURE 25.6
Videophones were part of the background that Hugo Gernsback, publisher of the first science-fiction magazines in the 1920s, used for his first science fiction novel. However, the cover artist's vision in this paperback still included a dial. (Courtesy of Fantasy Books)

Voice over Internet Protocol (VoIP)

Digitized voice can be sent as packets over the Internet.

Voice over Internet Protocol (VoIP) has become a favorite technology of market pundits and is offered by a number of companies. VoIP digitizes voice signals at the receiver and transmits them over the Internet as packets. One advantage is that sending Internet packets is much cheaper than using voice circuits. Another advantage is the potential of harnessing computers to process phone calls. These two features are pushing VoIP in opposite directions. One extreme is making cheap phone calls around the world from a computer, an approach that appeals to people with friends and family dispersed around the world. The other is feature-laden phones that turn voice messages into digital files that can be processed electronically. It remains to be seen how well the technology will live up to the considerable expectations of the pundits.

Packet delays can degrade voice transmission.

Quality of service is a serious issue in VoIP. Voice conversations are sensitive to delay, and packets transmitted over separate routes are subject to delay. The public Internet has only begun to adapt IPv6, which can assign special priorities to packets carrying voice signals; most nodes use the older IPv4, which treats voice packets like any other packets. The resulting transmission can be unintelligible. This problem can be avoided if telecommunications companies build their own IP networks using IPv6, and some companies have begun to do that. In this case, the IP lines simply replace SONET lines or other circuit-switched connections, and users should not hear much difference in their calls.

Another issue is compatibility with existing phones. Some VoIP systems require expensive special terminal equipment to use their advanced features. Others provide adapters that convert VoIP signals to the format required by standard analog phones. Extra features may be offered through computers, such as e-mailing digital voice-mail accounts.

Still other potential issues include the loss of features peculiar to the analog voice phone system. Because the phone network has its own power source, you can phone the power company to report an outage on an analog wire-line phone, but not on a cordless phone or a VoIP phone. Emergency 911 services require special equipment present on standard subscriber loops but not on VoIP networks.

Telephone service provided over cable-television networks faces many of the same issues as VoIP, and many cable networks use VoIP technology for their voice service.

Like any new technology, VoIP will have to convince customers that it's better than existing phone service. It may succeed in some niches but not others. Stay tuned.

Cellular versus Wire-Line Phones

Recently people have started to drop wire-line phones and use their cell phones as their main line. Typical examples are young, highly mobile people who are rarely at home to receive phone calls. It's not clear how far this trend will go. The convenience of cell phones is offset by their poorer sound quality and problems in finding a "sweet spot" to make a good connection to the cellular network. Cutting the cord to go all-cellular may not seem like such a good idea if your elderly rich uncle can't understand a word you say on your cell phone. On the other hand, cell phones are good backups for emergency calls or during power failures.

Video and "Triple-Play" Services

Convergence in telecommunications has led telephone and cable-television companies to talk about "triple-play" packages—combinations of voice, video, and broadband Internet connections. Cable companies have exploited this trend successfully to offer voice and data services, but phone companies have had trouble offering video service because their wires have limited bandwidth. Phone companies now offer video services in three ways:

"Triple-play" services offer voice, data, and video.

- Partnerships with satellite television companies, which compete with cable companies and can't offer voice service efficiently.
- *Video-on-demand* services offered over VDSL, which can switch video channels to individual subscribers. Video-on-demand could be packaged with satellite broadcasts so subscribers can request individualized programming as well as broadcast channels.
- *Fiber-to-the-home* (or premises) systems, which have dedicated bandwidth to carry video signals. Fiber can carry the full bandwidth of a cable network, putting phone companies on equal footing with cable companies, which have long had the lead in bandwidth. We'll look at this technology in the final section of this chapter.

Fixed Wireless Broadband Service

Fixed wireless broadband is a potentially competitive service that has been "just around the corner" for several years. This service installs fixed wireless transmitters in each neighborhood to transmit broadband signals—usually video and computer data—to subscribers. The goal is to avoid the high cost of stringing fiber or cable to each home.

The potential savings have attracted many companies from time to time, but the practical drawbacks have stalled deployment of the technology. The microwave frequencies that carry the signals are attenuated by rain and can be blocked by foliage, terrain, or buildings. In short, fixed wireless broadband may work well if you can see the transmitter from where you put your antenna, but you can't count on that.

Fiber to the Home or Premises

Verizon began fiber-to-the-home installations in 2004.

The narrow bandwidth of copper wires reaching individual homes has long limited the telephone network's ability to deliver telecommunications services to homes. DSL is part of a long-term effort to increase that bandwidth so phone companies can offer new services. Plans also include running fiber closer to individual subscribers.

Exactly how close the fiber should come to homes has been controversial. Although it seems logical to bring fiber all the way to the home, many analysts have been skeptical because of the potentially tremendous costs of overhauling the entire local telephone network. However, in the early 2000s rural phone companies and developers of large subdivisions began installing fiber-to-the-home systems. The large regional telephone companies have followed suit. Verizon began constructing its first system in Texas in 2004, with plans to run fiber past a million homes by the end of the year. Two other regional phone companies, SBC and BellSouth, have announced similar plans. Because this is a book on fiber optics, we will devote the rest of this chapter to fiber to the home.

The industry has developed a family of designs grouped as "fiber to the X" (FTTX), with *X* being a particular point in the network. Important variations are:

- *FTTB: Fiber to the Business* (or sometimes, Fiber to the Building)
- *FTTC: Fiber to the Curb* (near homes, but not all the way to them)
- *FTTD: Fiber to the Desk*
- *FTTH: Fiber to the Home*
- *FTTN: Fiber to the Neighborhood* (or Fiber to the Node)
- *FTTP: Fiber to the Premises* (equivalent to Fiber to the Home)

Spreading Fiber into the Local Phone System

There is wide agreement that the local phone system needs more bandwidth if it is to survive. The big questions are how much bandwidth, how best to provide it, and how to develop a future broadband network from today's limited telephone network. The central problem is the expense of replacing the existing network.

Fiber installation will cost $1000 to $1500 per home.

The existing telephone network is both an asset and a problem. It's an asset in that the phone companies have already built it and paid for it—but a problem in that its capacity is limited, and parts of it are aging. It's like an old computer that doesn't support the latest Web browsers and other newer applications. But the real problem is that replacing the existing network is very costly.

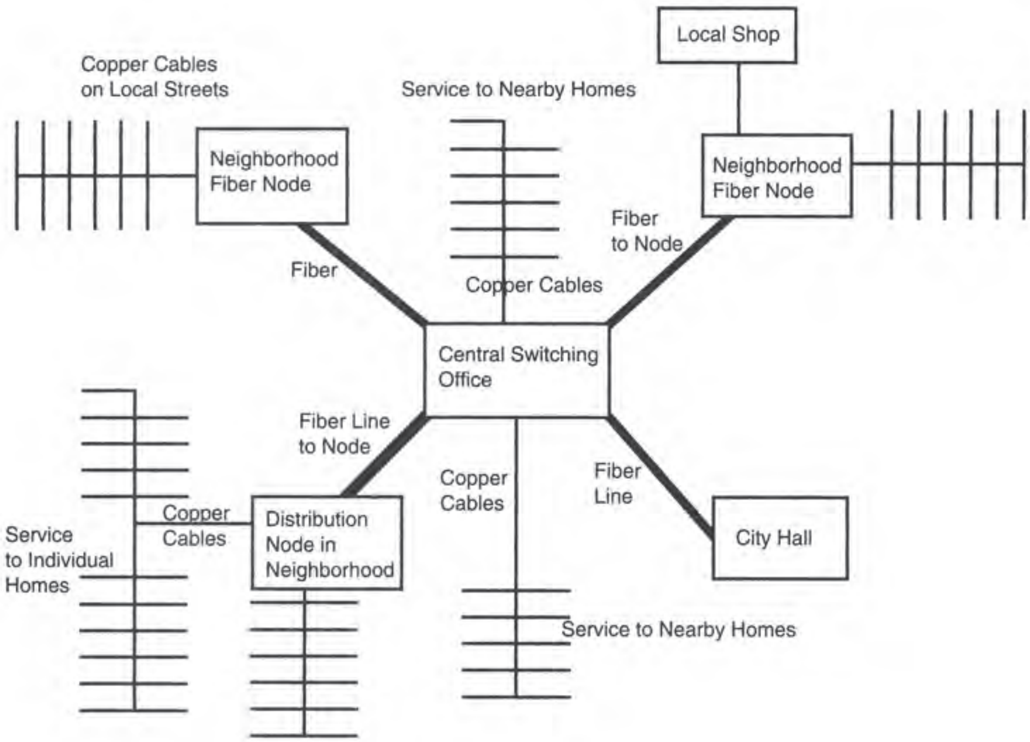


FIGURE 25.7
Fiber to the neighborhood.

Phone companies estimate that replacing existing local phone networks costs $1000 to $1500 per home. Fiber-optic equipment costs slightly more than copper wire, but most of the expense is the labor of installing new cables and equipment. Time is needed to run new cables along overhead poles and drop new lines to each home. Costly equipment and more time are required to replace existing buried utilities with new underground lines to each home. (It's relatively cheap to install fiber along with other utilities in new developments because the holes are already in the ground.)

The sheer scale of the job makes it a budget-buster for phone companies, so they are phasing in fiber. Fiber networks have gradually spread out from switching offices to serve neighborhood nodes. Separately, phone companies plan to replace existing distribution networks gradually with fiber, one neighborhood or community at a time.

Fiber to the Neighborhood

Today's telephone networks use fibers to connect remote neighborhoods to the local distribution system, as shown in Figure 25.4. The next logical step is *fiber to the neighborhood (or node)*, or FTTN, shown in Figure 25.7. High-speed fiber distributes signals to neighborhood nodes, which transfer the signals to copper wires that run along local streets and distribute signals to individual homes. An FTTN node might serve a few hundred telephone subscribers, including small local businesses. Similar fiber nodes service business and government, like the City Hall at the lower right in Figure 25.7. Copper cables run from the switching office to serve its immediate neighborhood.

FTTN nodes serve hundreds of subscribers.

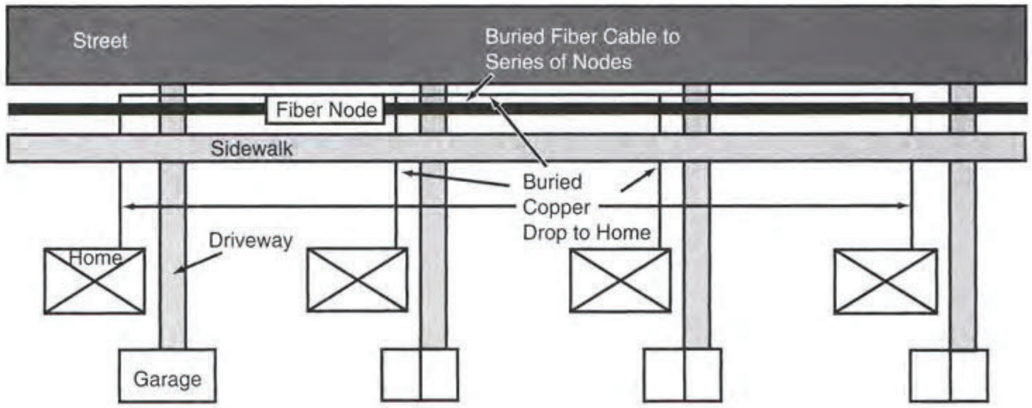


FIGURE 25.8
Fiber to the curb.

Fiber to the business (or building in the sense of apartment building) fits into a fiber-to-the-node system, with some of the nodes located at office and apartment buildings rather than in residential neighborhoods.

FTTN can be adapted to transmit and distribute DSL digital signals separately from phone calls to the node, which rearranges the signals to add DSL to phone lines.

Fiber to the Curb (FTTC)

Fiber to the curb is used with high-speed VDSL.

Fiber to the curb runs fiber down every street, ending at a curbside distribution node in front of the homes. Copper drop cables run from the curbside node to every home, as shown in Figure 25.8. In this example, an add-drop multiplexer connects a buried fiber cable to a curbside service node, typically a weatherproof box slightly larger than a standard television that sits on the ground near the street, like a fire hydrant. Buried copper cables run from the box to homes on the block. If the neighborhood has aerial cables, the distribution node may hang on a utility pole.

Typically the FTTC node is less than a thousand feet (300 meters) from homes, close enough for short twisted-pair copper drops to carry high-speed VDSL signals between the fiber and the home. This allows the telephone network to deliver up to 52 Mbit/s to homes, enough to carry a few video-on-demand channels, but not enough to deliver the whole spectrum of cable-television signals to homes.

FTTC curb networks have been built in some areas, but their future is unclear. They may be a stopgap on the way to fiber to the home.

Fiber to the Home (FTTH)

Demand for Internet bandwidth pushed home fiber development.

Telecommunications visionaries have been thinking about fiber to the home (FTTH) since 1972, when John Fulenwider first suggested the idea for a wired-city project being studied by General Telephone and Electronics. The first experimental system, called Hi-OVIS, began operation in 1978 in Higashi-Ikoma, Japan. Canada, France, and a few U. S. telephone companies tested fiber to the home in the years that followed. In most cases, the technology worked, but the economics didn't. No one found a combination of services that could generate enough income to justify the high cost of installing fiber to every home.

Today several trends have combined to shift the balance toward fiber to the home. Over the past 20 years, personal computer users have gone from 1200 bits/s dial-up modems to broadband DSL or cable-modem connections at speeds exceeding 1 Mbit/s. This tremendous increase in raw speed has been offset by bloated computer files and the increasing richness of features like streaming video and audio on the World Wide Web, which drive the demand for more bandwidth. Like the household clutter that fills closets, information needs continue to expand indefinitely.

The prices of optical equipment have dropped, and the technology for fiber installation has improved. For example, companies specializing in fiber-to-the-home systems have developed factory-terminated drop cables, so technicians can plug cable into sockets on a home terminal without cutting it and installing connectors or splices. These improvements have reduced the cost of installing new fiber networks to only about 5% to 10% more than that for copper networks. This trend makes fiber extremely attractive for new installations.

Fiber cables are more reliable in harsh outdoor environments. Fibers are not as vulnerable to moisture as copper. Passive optical networks also eliminate the need to install active components outdoors, which are a major cause of failure of copper cables.

Regional wire-line phone companies are under intense competitive pressure. Their total number of voice lines has decreased as subscribers turn entirely to cell phones, or shift their second line from a wired phone to a cell phone. They need more bandwidth so they can offer video and compete head-to-head against cable companies.

Many early home fiber installations were in rural areas.

The current wave of fiber-to-the-home installations began with publicly owned rural utilities and suburban developers. Large phone and cable companies lagged badly in bringing broadband Internet access to rural areas, some of which had little or no cable service and poor dial-up connections. Public utilities and telephone cooperatives decided to fill the gap. Run by local governments or cooperatives, they didn't have to answer to stockholders. Residents who paid for the services would get the benefits themselves. Some believed they needed better telecommunications to promote development in their areas. Government loan programs encouraged their investment.

Developers building higher-end housing also saw benefits in fiber to the home. Laying fiber wasn't excessively expensive because they had to provide telephone service for many newly built homes or apartments. They quickly discovered that advanced telecommunication services could help them sell their houses at higher prices—and satisfy the needs of the buyers.

FTTH lets phone companies offer voice, data, and video.

The big phone companies were latecomers to FTTH. They had talked about fiber-to-the-home systems before, but had stopped short of investing serious money in new equipment. But that changed as competitive pressures increased and the cost differential between fiber and copper dropped. New versions of home fiber networks are based on industry standards—an important feature for phone companies that want a choice of equipment vendors. These new designs can transmit cable-television services as well as voice and data, so phone companies can offer "triple-play" services. Government regulations have changed, and the phone companies have realized that DSL is only a stopgap unlikely to meet long-term needs.

Verizon's starting point for "fiber to the premises" systems was Keller, Texas, a town of 16,000 homes and 33,000 people just west of Dallas. Verizon promised to lay fiber past one million homes by the end of 2004, and twice that many in 2005. Other large phone companies have yet to start installing home fiber systems, although Bell South and SBC have said they will. But don't expect fiber to come to your house tomorrow. With more than 100 million households in the United States, changing five million homes a year to fiber would take 20 years.

Verizon plans to pass a million homes by the end of 2004, but doesn't specify how many homes will be connected to fiber then. Making the connections takes more time and costs

Old copper phone lines will remain in service.

more money, because phone companies first want to test how the fiber systems work and how customers respond. Verizon is starting in Keller because the town has strong competition and overhead cables, which are easier to replace than buried lines. The installation schedule will depend on competitive pressures and the condition of existing phone lines. The high-speed broadband service possible over fiber will come at a premium price.

The new fiber systems will overlay the old copper phone networks, which will remain in place with customers connected to them. The shift to fiber will be gradual, spreading company investment over time. As customers upgrade to broadband Internet or video services, Verizon plans to shift them to the fiber connection, which has the bandwidth needed for those services. Only at that point will the phone company run the fiber-optic drop line and hook up the home optical interfaces. Customers also may be shifted to the fiber system if the copper lines go down. Telephone engineers expect the fiber systems to work better than conventional phone lines because they should be less vulnerable to failures of outdoor electronics and moisture damage.

A major performance concern with home fiber connections is powering the phone service. Copper phone lines carry a 48-volt bias voltage that standard phones need to operate. (Cordless phones and many electronic phones require power from local electric lines.) Most designs for home fiber links rely on local electric power with a battery backup, which requires users to monitor batteries and limits phone operating time in the event of a power failure. How customers will regard this issue remains to be seen.

Two fundamentally different approaches are being used for FTTH systems: passive optical networks and Gigabit Ethernet networks. Let's look at the two in detail.

Passive Optical Networks

Passive optical networks have no active components between switch and subscriber.

The *passive optical network* or PON design reduces installation and operating costs by eliminating active components between the transmitting terminal and the subscriber. In its simplest form, shown in Figure 25.9, an *optical line terminal* sends downstream signals through a fiber with a splitter that distributes the signals among as many as 32 output fibers, one for each home served. As in local-area networks, all signals reach all terminals, but each terminal pays attention only to the signals directed to it. Signals may be shared among all terminals or directed to only one. *Optical network terminals* at the home contain transmitters that send signals upstream at a slower data rate. The result is a two-way point-to-multipoint network.

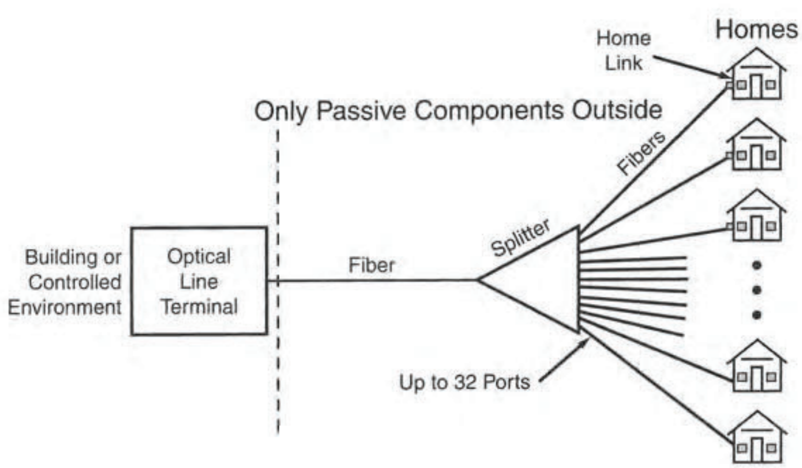


FIGURE 25.9
Simple passive optical network.

Note that only fibers, couplers, and connectors—purely passive components—are used in the outdoor distribution network. Transmitters and receivers are installed only at the end points, typically the switching office and the home. No electrical power runs along the fiber-optic cable, and no active optics or electronics are exposed to hostile outdoor operating conditions. This reduces both maintenance and operating expenses, important issues for phone companies.

Passive splitters divide signals among up to 32 output fibers.

Downstream signals come from a single transmitter, which generates enough power to be shared among up to 32 output ports. In general, the downstream transmitters are relatively expensive, but their cost is shared among many receiving units. Many more upstream transmitters are needed—one per house—so they must be inexpensive. Upstream transmitters typically operate at 1310 nm, where light sources are inexpensive.

Upstream signals return through the passive network to a single receiver at the optical line terminal. The upstream signals are separated from each other by assigning separate time slots to each home transmitter, so only one transmits signals upstream at a time. Upstream and downstream signals are separated by wavelength-division multiplexing, with upstream transmission at 1260 to 1360 nm, and downstream transmission at longer wavelengths from 1480 to 1550 nm. Table 25.2 lists important features of three standards covering PONs.

Video cable service will overlay digital traffic on phone company fiber systems.

Major U.S. telephone companies picked the ITU G.983 *Full Service Access Network (FSAN)* standard for their FTTP systems. G.983 specifies three types of transmission through the network at three different wavelengths.

- Downstream analog (cable-television) video transmission at 1550 nm, where erbium fiber amplifiers can amplify video feeds from external sources
- Downstream data transmission at 622 Mbit/s at 1480–1500 nm using local transmitters, which don't require amplification
- Upstream data transmission at 155 or 622 Mbit/s near 1310 nm

Table 25.2 ITU Standards for PONs

Name	BPON (Broadband PON or Full Service Access Network)	GPON (Gigabit PON)	EPON (Ethernet PON)
Standard	ITU G.983	ITU G.984	IEEE 802.3 ah EFM
Data packets	ATM	ATM or Ethernet	Ethernet
Downstream bandwidth	622 Mbit/s	1.25 or 2.5 Gbit/s	1.25 Gbit/s
Upstream bandwidth	Total 155 or 622 Mbit/s	Total 155 or 622 Mbit/s or 1.2 or 2.5 Gbit/s	1.25 Gbit/s
Downstream wavelengths	Data 1480–1500 nm, video 1550 nm	Data 1480–1500 nm, video 1550 nm	1550 nm
Upstream wavelengths	1260–1360 nm	1260–1360 nm	1310 nm

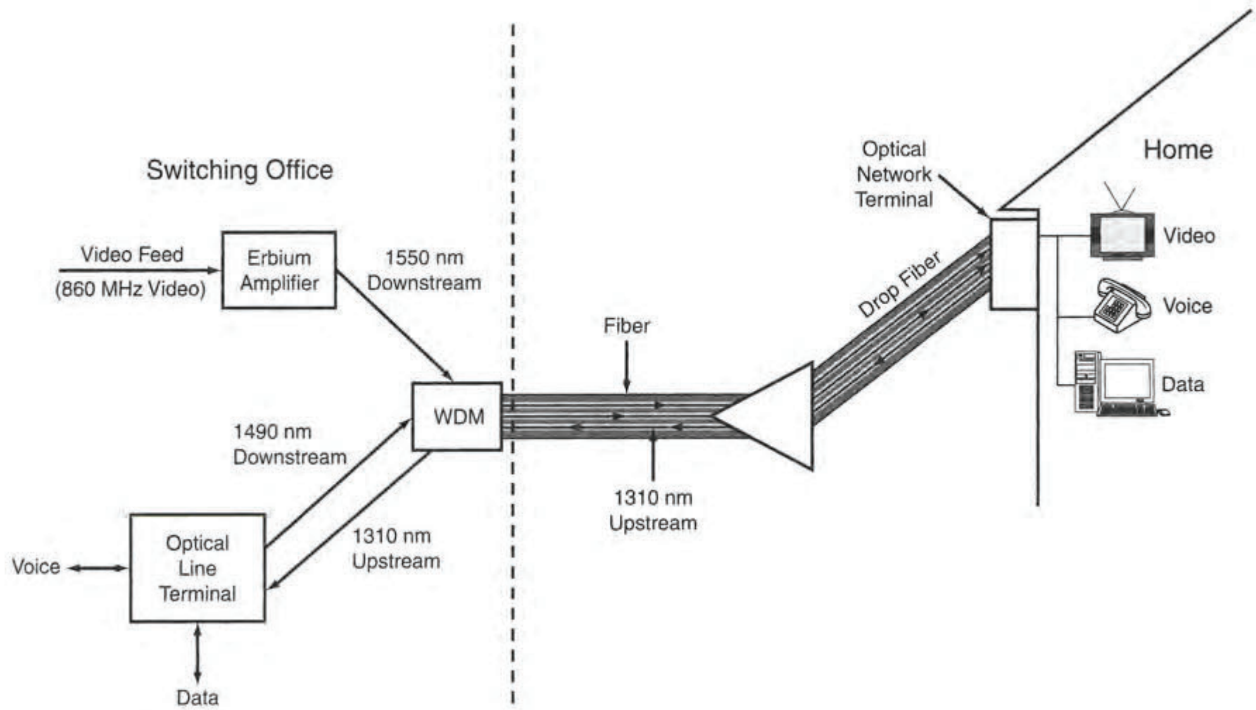


FIGURE 25.10

Signal transmission in the Verizon home fiber network.

Both the upstream and downstream data transmission capacities are shared among the users connected to the branched fibers. Voice signals are included in the digital data streams. Figure 25.10 illustrates the arrangement used by Verizon.

Video transmission in the Verizon system is in the standard 860-MHz band used for cable television networks, which can carry data plus analog and digital video signals. The FTTH system uses the downstream channel only for video transmission. You'll learn more about this format in Chapter 27.

Verizon transmits both upstream and downstream data as 53-byte ATM cells, a format widely used by local telephone companies because it can guarantee a fixed data rate for voice, as well as carry packets from data networks. At this writing, phone companies have not yet specified what data speeds they will offer, although they will likely be a series of levels carrying different prices. The system can offer multiple circuit-switched phone lines. In practice, each fiber on the splitter can carry a different data rate, determined by the customer's needs and budget.

The splitter in 32-channel PON attenuates signals by 15 dB.

Alternatively, data signals can be transmitted in Ethernet or Internet Protocol formats. The ITU G.984 standard specifies this for Gigabit PONs, while the IEEE 803.2 AH standard specifies it for EPONs. The two systems differ in detail, with more splitting possible in GPON networks, which unlike EPONs can support ATM transmission.

The splitting of signals among 32 potential output lines in BPON corresponds to a 15-dB drop, and requires higher-power transmitters at the switching office than at the home. Input video signals come in optical format and are amplified optically; all homes receive the same video signals, although special decoders are required to view premium channels. Data signals are generated locally by the optical line terminal, which combines input data streams from voice and data networks and addresses the signals to individual home terminals.

Fiber loss is much lower in the upstream direction because the signals are not split, so home terminals—called *optical network terminals*—need lower-power data transmitters. The optical line terminal serves as the central controller for all home terminals on a group of branching fibers. It assigns each home terminal its own time slot for upstream transmission using the *time-division multiple-access* (TDMA) protocol. Each home terminal switches on during its assigned time slot, then switches off so the next can begin transmitting. Clock signals transmitted downstream synchronize the subscriber terminals, dividing upstream capacity among users and preventing transmitters from sending signals at the same time. Each home terminal is at a different distance from the central transmitter, so the system measures those distances and programs appropriate delays into its control signals. The need to control these delays limits maximum transmission distance to 20 km.

Different fiber arrangements are possible. The BPON and GPON standards allow for either one or two fibers to serve each home; in single-fiber systems signals are transmitted in opposite directions simultaneously, but at different wavelengths. A single fiber can be split into up to 32 output fibers, but splitters with fewer ports can be used when data rates or attenuation are high. Two small splitters can be arranged in series, so each output of a 1×4 splitter could be followed by a 1×8 splitter, yielding a total of 32 possible outputs.

Point-to-Point Ethernet in the First Mile

Point-to-point links are between Ethernet nodes and terminal boxes.

The leading alternative to the PON is point-to-point Gigabit Ethernet transmission through interface units that connect to each home. As shown in Figure 25.11, signals travel through an Ethernet node that receives input signals from the outside world and distributes them to the proper destinations through single fibers linked to separate homes. The figure shows how the system can work in a rural area where large distances separate subscribers, making the high losses of PON splitters a problem.

Like Ethernet PON, point-to-point Ethernet transmission is defined in the IEEE 802.3 AH EFM standard. Like the standard, the industry jargon lumps both networks together as *Ethernet in the first mile*, reflecting the idea that the network starts in the home. Yet the two have important distinctions in network structure and transmission capabilities.

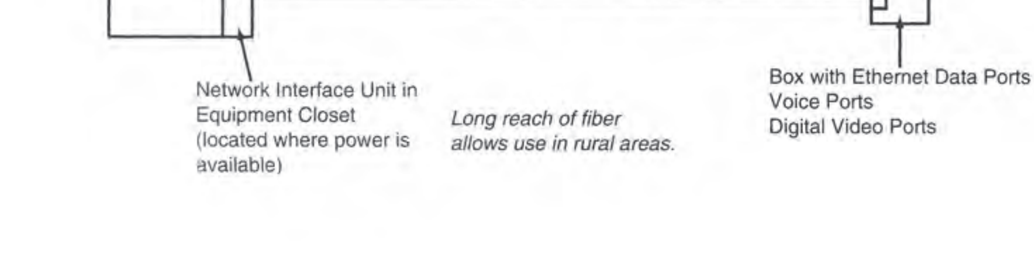


FIGURE 25.11 *Gigabit Ethernet to the subscriber.*

In the point-to-point network, all fiber links are strictly point-to-point, between Ethernet nodes and terminal points. No splitters divide optical signals; all signals go between pairs of electro-optic boxes. This is the architecture used in office local-area networks, and it allows the use of standard low-cost mass-produced Ethernet equipment. Ethernet nodes are active components that require electrical power, but they can be placed in utility closets in buildings, with long single-mode fiber connections running to individual homes that could be kilometers away. As Figure 25.11 shows, an Ethernet node serving a small town can be installed in a closet or storage area in a general store or municipal building.

As in PON networks, all subscribers attached to that node share a single input data stream. However, a pure Ethernet system is far more flexible in handling variations in the data rate. If nobody else is using the system, a Gigabit Ethernet system can deliver data to a single home at 1 Gbit/s. In contrast, PONs limit the maximum data transfer rate to a lower level, and must reserve fixed capacities for some users.

Large telephone companies have been slow to use point-to-point Ethernet, but some smaller companies and public utility districts have chosen it for their home fiber networks. With its high bandwidth, point-to-point Ethernet has the capacity to handle video transmission, security monitors, video cameras, and Internet links to appliances, as shown in Figure 25.12. Time and market reaction will be the acid tests of point-to-point Ethernet technology.

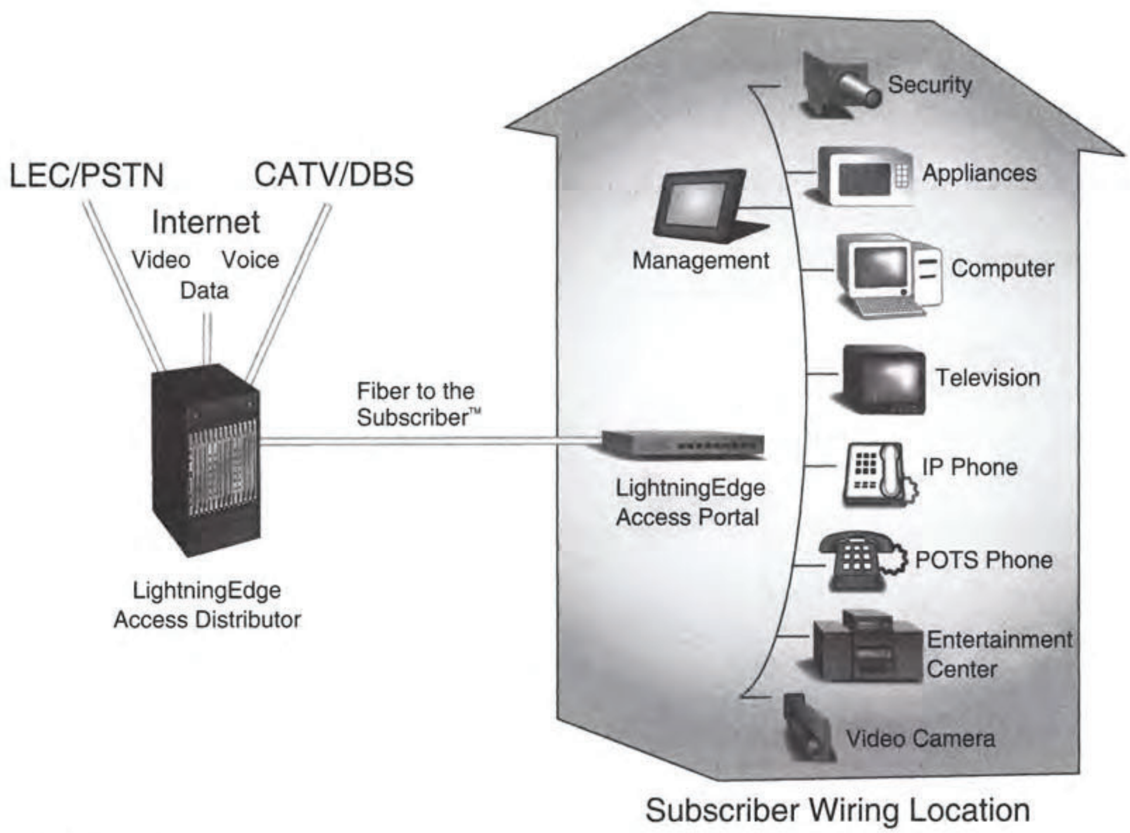


FIGURE 25.12
Multiple services delivered over Gigabit Ethernet link. (Courtesy of World Wide Packets)

THINGS TO THINK ABOUT

Timing of Fiber to the Home

In the March/April 2000 issue of *Technology Review* magazine, I described how fiber to the home might be used—but I set my example in the year 2020. Was I way off in my estimate of when fiber would be installed at homes?

Not really, for various reasons that are worth thinking about.

First, I described a family using technology that had become common by 2020. They could have been using it for years, taking advantage of improvements as we have taken advantage of improvements in personal computers.

Second, and more important, it will take time for fiber to reach homes all across the country. It's a huge job to rebuild a network serving over 100 million households. Verizon is starting by running fiber past a million homes in 2004 and plans to pass 2 million homes in 2005. But all those homes won't automatically be connected to the fiber network. Individual subscribers will have to sign up for video and/or data services that require the fiber connection, and they will need time to decide whether the service is worth the price. And cable companies may decide to run fiber to homes if they see a market for the extra bandwidth.

People don't sign up automatically for all new services. It has taken years for broadband Internet links over cable modems and DSL to reach about a third of American households, although they are available to most of the population. Cable television has been widely available for 25 years, but the fraction of households that subscribe is stuck below 70% (not counting satellite television), compared to more than 90% who have VCRs.

For now, I'm happy with my guess of 2020. How do you expect fiber to the home to grow?

Ethernet to the subscriber will compete with passive optical networks for other types of signal distribution as well as fiber to the home. Some of the earliest Gigabit Ethernet networks were installed by Canadian school systems as part of a program to enhance Internet connectivity to schools.

What Have You Learned?

1. The subscriber loop distributes telephone signals to individual users. The access network is a new term for the network that distributes services to business users.
2. The subscriber loop distributes signals from a switching office or central office to individual users over copper and fiber cables. The switching office is the interface between individual phone lines and the global network.
3. Twisted pairs of copper wires are widely used in the subscriber loop. They can carry voice signals several miles, but DSL is limited to shorter distances.
4. Traditional phone lines were designed to carry only analog voice signals at 300 to 3000 Hz called Plain Old Telephone Service (POTS).
5. Fax machines and dial-up modems transmit digital data by converting the data to analog tones and transmitting the tones over voice phone lines.

6. Digital Subscriber Line (DSL) transmits data on twisted-pair phone lines at frequencies above the normal voice range.
7. Several types of DSL transmission have been developed; they differ in nominal data rate and maximum transmission distance. The maximum speed drops with total transmission distance, measured along the cable route.
8. Voice over Internet Protocol (VoIP) sends digitized voice as packets over the Internet. This cuts costs and allows new services, but packet delays can degrade voice quality.
9. Cell phones are replacing wireline phones for some people.
10. Local cable and phone companies want to offer "triple-play" services that combine voice, video, and data.
11. FTTX is a family of services that run fiber in the subscriber loop, including fiber to the neighborhood (FTTN), fiber to the curb (FTTC), and fiber to the home (FTTH) or premises (FTTP).
12. FTTN nodes serve hundreds of subscribers in a neighborhood. They can distribute DSL to subscribers if the data signals are transmitted to the nodes separately from the phone calls.
13. FTTC runs fiber to nodes on each block, with short connections to homes that can carry high-speed VDSL.
14. Early fiber-to-the-home installations were in rural areas that lacked broadband service and large new developments where fiber was laid along with new utility services.
15. Demand for Internet bandwidth and interest in offering "triple-play" services led large phone companies to start installing fiber to the home. The fiber is being overlaid, with the old copper lines remaining in place. Customers are hooked up to fiber if they sign up for new services.
16. Passive optical networks distribute FTTH services. They have no active components between switch and subscriber, reducing operation and maintenance costs. Passive splitters distribute signals to up to 32 output fibers.
17. ITU G.983 and G.984 standards cover two types of passive optical networks, specifying how they transmit downstream data, upstream data, and video overlays at separate wavelengths.
18. Point-to-point Gigabit Ethernet systems also can transmit signals to homes, with distribution through neighborhood Ethernet nodes. This allows use of inexpensive Ethernet components.

What's Next?

In Chapter 26, you will learn about data transmission and local-area networks.

Further Reading

DSL Reports: *http://www.dslreports.com*

Ethernet in the First Mile Alliance: *http://www.efmalliance.org*

Fiber to the Home Council: *http://www.ftthcouncil.org*

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

Questions to Think About

1. A switching office serves 5000 voice telephone lines. It is designed so that at peak usage 20% of the lines can be connected—a total of 1000 phone lines. Residents discover the Internet and 500 of them buy dial-up modems and install new phone lines so they can leave their modems on all of the time. How much more switching capacity does the phone company have to install, both in number of lines and percent?
2. Suppose that instead of installing new phone lines, the residents of the town in Question 1 hooked their modems up to existing phone lines. If 500 people buy modems and half of them go on the Internet in the evening at a time of peak residential calling, how much does the phone company have to increase its switching capacity? How much must switching capacity be increased to accommodate half of the households buying modems and half of the modem users going on the Internet in the evening? Assume the rate of voice calling does not change.
3. Check to find how far your residential phone line is from your local phone company's switching office at *http://www.dslreports.com.* What DSL rates are available? If you're in a class, compare the rates and distance with those of other students.
4. A fiber-to-the-curb system is installed on a street. It serves 10 homes with copper drop cables less than 1000 feet long, which carry one phone line plus VDSL service at the maximum possible speed. If all voice and data services to the curbside interface are digitized and transmitted on a fiber, what is the minimum data rate on the fiber needed to serve all homes.
5. A passive optical network serves 32 subscribers with 622 Mbit/s downstream and 155 Mbit/s upstream. Two customers buy premium service, which guarantees 50 Mbit/s downstream and 10 Mbit/s upstream. What speed can the other customers get if the remaining capacity is divided equally among them?
6. The transmitter for a passive optical network generates a 1-mW signal that is divided equally among 32 users. If the cable loss is 10 dB and the couplers have no excess loss, what is the signal that reaches each user?
7. A Gigabit Ethernet signal is split among 32 subscribers. Neglecting losses arising from congestion, what is the maximum data rate if all are receiving signals at equal capacity?

Chapter Quiz

1. Which of the following is at the network edge?

a. individual telephone subscribers

b. Digital Subscriber Line

c. individual telephones

d. telephone switching offices

e. international connections from national telecommunication networks

2. The network edge is the

a. interface at which calls are directed.

b. point where digital signals stop.

c. point where telephone signals stop at a telephone.

d. point where signals are transferred between regional and long-distance networks.

e. point where signals are transferred between long-distance and international networks.

3. What connects to standard voice telephones?

a. optical fibers

b. twisted-wire pairs

c. single copper wires

d. coaxial copper cable

e. special hybrid cables with one fiber and one copper wire

4. What transmits digital subscriber line (DSL)?

a. optical fibers

b. twisted-wire pairs

c. single copper wires

d. coaxial copper cable

e. special hybrid cables with one fiber and one copper wire

5. Which of the following can limit the availability of DSL services?

a. load coils

b. distance from the central switching office

c. quality of phone lines

d. installation of digital loop carriers

e. all of the above

6. You are in charge of telephone operations for a resort town. The CEO of your company has bought a vacation home in a new development outside of DSL reach, but wants at least 1.5-Mbit/s ADSL service to keep in touch with corporate headquarters. What's the best way to upgrade service to the whole new development and please the big boss?

a. run fiber-optic cable to the CEO's door
b. run fiber to the center of the new development and build a new node to distribute DSL and other services there
c. install IDSL because it can reach farther than ADSL
d. run VDSL from your switching office
e. start looking for a new job because you're not going to be able to do it

7. What services besides POTS are transmitted in the low-frequency analog band of copper twisted pair?

a. digital switched video
b. DSL
c. fax and dial-up modem signals
d. Gigabit Ethernet
e. passive optical networks

8. Each node in a fiber-to-the-curb system would serve about how many homes?

a. 1
b. 10
c. 100
d. 500
e. over 1000

9. Each node in a fiber-to-the-neighborhood system would serve about how many homes?

a. 1
b. 10
c. 100
d. 500
e. several thousand

10. What unique service is offered only by fiber to the home?

a. high-definition digital television
b. Internet access at faster than 10 Mbit/s
c. combination of voice, video, and data at speeds faster than cable modems
d. high-definition video telephone
e. none of the above

11. The high cost of installing fiber to the home in communities that already have telephone service on copper wires comes mainly from

a. labor costs of installation.

b. the high cost of optical terminals.
c. the cost of removing old copper phone wires.
d. the need to secure new right of way to lay fiber.
e. lobbying to change regulations affecting telecommunications.

12. What equipment is installed outdoors in a passive optical network?

a. fiber-optic cable only
b. fiber-optic cable and splitters only
c. fiber-optic cable and optical line terminals only
d. fiber-optic cable, splitters, and optical switches only
e. fiber-optic cable, splitters, optical line terminals only

13. Signals transmitted downstream in a single fiber leaving an optical line terminal in an FSAN (ITU G.983) passive optical network can be divided among up to how many fibers going to individual homes?

a. 1
b. 4
c. 8
d. 16
e. 32

14. How do passive optical networks transmit video signals downstream to homes?

a. All video channels are digitized and added to the Internet data stream.
b. as an overlay signal in analog cable television format at the same 1310-nm wavelength as signals transmitted upstream from home terminals
c. as an overlay signal in analog cable-television format at 1550 nm
d. One channel selected by the subscriber is transmitted in the Internet data stream to each television set in the home.
e. All video signals are digitized and transmitted in a separate data stream at 1550 nm.

15. The maximum data rate a point-to-point Gigabit Ethernet system can deliver over a single fiber to the home subscriber is

a. 10 Mbit/s.
b. 52 Mbit/s.
c. 100 Mbit/s.
d. 622 Mbit/s.
e. 1 Gbit/s.

CHAPTER

26

Internet Access and Local-Area Networks

About This Chapter

Computer data transmission differs in fundamental ways from standard telephone voice transmission. One is that computer data flows in bursts, whereas voice traffic travels at a steady rate. This means that voice and data signals are handled differently. Although voice and data share major parts of the global telecommunications network, networks optimized for data are designed differently. This chapter covers data networks and the transmission technologies they use, then describes the networking standards that specify fiber-optic transmission.

Data and Voice Transmission

The first data networks appeared in the 1960s, when universities and other large organizations installed data terminals connecting directly to large mainframe computers. Thus users didn't need to bring tapes or decks of punched cards to the computer center. Interactive computing grew quickly, leading to proposals for systems that would allow people without their own computer to access remote computers over phone lines. At the same time, the Defense Advanced Research Projects Agency (DARPA) began interconnecting computers at major research universities and government laboratories so they could share resources.

Early data networks linked simple teletype machines to mainframe computers. Teletypes basically were little more than electronic keyboards that printed data sent to and from the mainframe on a roll of paper. Such terminals later were called "dumb" terminals because they lacked any computer power of their own. The emergence of the personal computer changed the picture because it could process information without a

Early data networks linked dumb terminals to mainframe computers.

mainframe. Users of personal computers developed software and hardware to send data and messages to each other over voice telephone lines. When companies began buying personal computers, and installed local-area networks so users could share data and access information on mainframe computers.

The first networks were private or proprietary, with the DARPA-sponsored "internetwork" available only to university and government computer labs. Computer users wanted to be able to communicate with everyone who had a computer, so they pressed for more connectivity between networks. As a result, the government-university "internetwork" evolved into the Internet, and development of the World Wide Web made the Internet a vital resource that we take almost for granted today.

Like the voice telephone network, the Internet has become global.

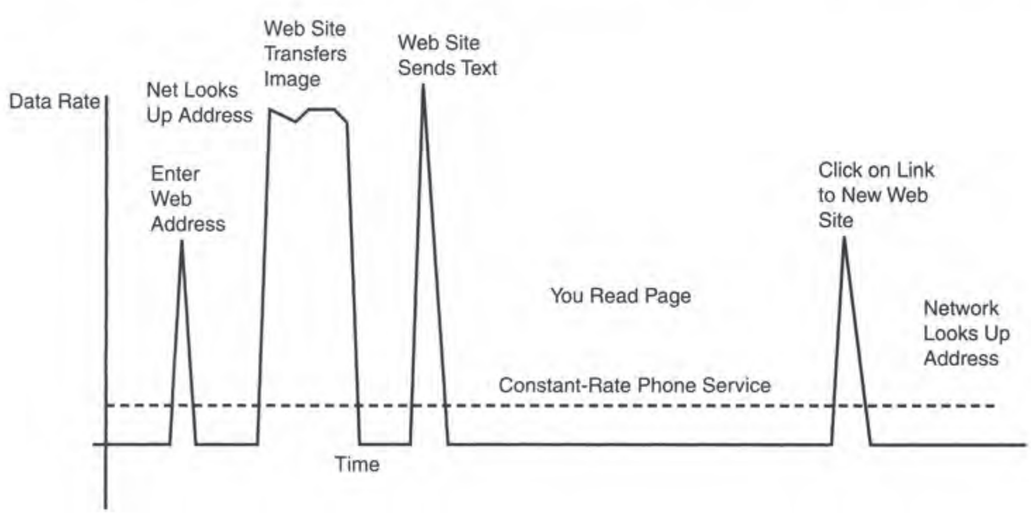
Nature of Data Transmission

Data transmission is bursty.

Most data transmission comes in short bursts, as you can see if you watch your own activities on your computer. When you browse the Web, you first enter a web address, which your computer transmits. Then you wait for a remote server to look up the Web page and request the site to send you information. The site may send you data in two or more blocks, as in Figure 26.1 where it transmits a large image file and a block of text. Then you read the downloaded Web page—with no traffic to and from the Internet—until you click on a link to a new Web site. You see the same pattern when you read e-mail or download files; brief periods of data transmission separated by long periods of inactivity. This type of data transmission is called *bursty* data.

All bursts are not the same size. Entering a one-line Web address may trigger the transfer of a one-megabyte graphic image on the Web site's home page. One e-mail may be a single sentence inviting you to lunch, and the next a two-megabyte report. Smoothing this uneven traffic flow requires a data link that has a very high bandwidth at any given instant, but not all the time. In contrast, standard voice telephones provide a fixed transmission capacity for the entire duration of a call, whether or not anyone is talking. This ensures that

FIGURE 26.1
Bursty computer data on a web link.



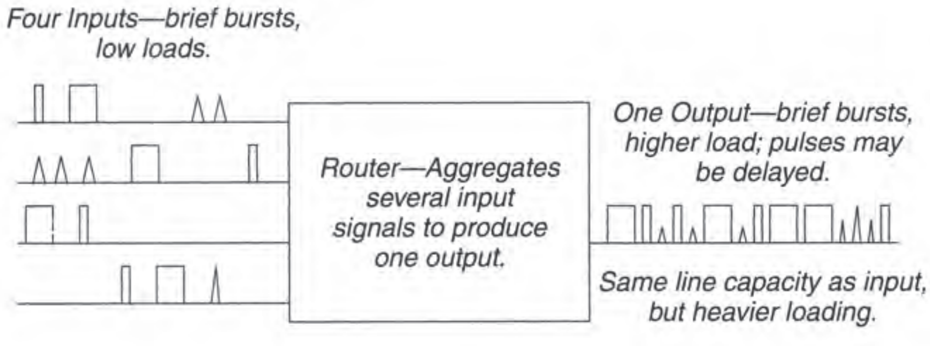


FIGURE 26.2
Aggregation of signals in a data network.

the capacity is available for speakers to use immediately. (Voice over Internet Protocol works differently, as you learned in Chapter 25.)

Packet switching works well with bursts of data.

To accommodate bursty data transmission, data are transmitted and switched in packets, as you learned in Chapter 19. Each data packet includes a header, which carries the destination address and other routing information. Individual data network connections can transmit signals at high peak speeds, but the network design assumes that the average connection transmits data only a small fraction of the time, so its overall load is low. Figure 26.2 shows how this packet switching principle packs data from several high-capacity, low-usage lines into a single high-capacity, high-usage line.

The transmission of data packets is irregular, so one packet can arrive while another is being transmitted, or two packets can arrive at the same time. Most older data-transmission protocols simply queue the input packets and transmit them in the same order as they arrived. This works fine with most communications software, which can tolerate delays in data packet transmission. However, some services, notably voice, are sensitive to time delays as we notice when voice and pictures in a video or movie slip out of synchronization. To cope with delays, some newer protocols assign different *priorities* to packets depending on the service they carry. Thus packets carrying voice signals can have the highest priority and go straight through the system, just as if they had a reserved channel.

Data Network Protocols and Layers

Like telephone networks, data networks have their own standards and *protocols*, which determine how signals are transmitted. The protocols determine things like data formats and packet sizes. Some allow data packets to vary in length; others require a standard length for all packets. Likewise, the protocols specify the information that headers carry, so the network can interpret data in a consistent manner.

Data network protocols are arranged as a stack of layers.

As you learned in Chapter 20, data-transmission standards are arranged as a stack of layers. Figure 26.3 shows the layers for computer networks and their associated protocols.

Your computer is at the top of the stack. When you send e-mail, an application on your computer (layer 7) prepares the messages and monitors how they flow from and to your computer. Protocols, such as SMTP (simple mail transfer protocol), that the server uses to handle your e-mail are in layers 5 and 6. Farther down in layer 4 are the transmission

FIGURE 26.3
Layering and computer network protocols.

Layer Designation	Protocols
7 Application	Electronic mail, file transfer, etc.
6 Presentation	Various protocols, SMTP (simple mail transfer protocol), FTP (file transfer protocol), etc., span both layers.
5 Session	
4 Transport	TCP (transmission control protocol)
3 Network	Internet protocol (and others)
2 Data Link	Network-specified protocols (Ethernet, etc.)
1 Physical Layer	Stream of bits (SONET, etc.)
WDM and optical layer are down here.	

control protocol (TCP) settings that determine how your computer and the server transmit signals to each other, and Internet Protocol (IP) settings (layer 3) that affect transmission on the rest of the network. All the layers typically are handled in software. The physical format for data transmission over your local network is set by the Data Link standard in layer 2; Ethernet is a typical example. The physical format of the data in the global telecommunications network is set on layer 1, the physical layer. As you learned earlier, the data packets from each layer are packaged into packets for the next lower layer at the transmitter end; at the receiver end the data packets travel up the stack to your computer.

The Internet and Its Structure

Like the global and national telecommunications networks you saw in Chapter 23, the Internet has a complex structure. Small networks feed into larger ones, which in turn feed into a high-capacity *backbone system*. We won't go into detail, but you should understand this basic structure.

The Internet Backbone

The Internet backbone is a network of high-speed transmission lines between major nodes called *Points of Presence* or *POPs.* Figure 23.12 showed one backbone system; Figure 26.4 shows another.

The Internet backbone links POPs.

Routers at POPs direct packets from the input port to a POP that is nearer to the packets' ultimate destination. The routers work on IP packets at the network layer, reading headers and transferring the packets to the physical layer. There the packets are converted to a stream of data bits and transmitted through fiber to the next POP. At the final POP, the bit stream is converted back into IP packets for delivery to their ultimate destination. This process is repeated for every packet. It may sound inefficient, but it actually uses transmission lines more efficiently.

Comparing the Internet backbone map of Figure 23.12 with the same carrier's telecommunications backbone map in Figure 23.11 shows that Internet POPs are analogous to major urban switching centers, which are nodes on long-haul networks. POPs are the points where Internet traffic enters and leaves the Internet backbone system. Long-haul switching centers serve the same purpose in the telephone network. A variety of carriers operate regional Internet networks. These connect to local points of presence, which link to individual users.

POPs are analogs of major urban switching nodes.

Internet Connectivity

Homes and offices connect to the Internet in a variety of ways, including:

- Dial-up modem connections over voice telephone lines
- Digital Subscriber Line (DSL) over twisted-wire phone lines
- Cable modem (described in Chapter 27)
- Organizational metropolitan-area and local-area networks, which link many computers in a building or within an organization
- Wireless local-area networks and hot spots
- Terrestrial microwave links
- Satellite data links
- Fiber-to-the-home systems
- Wireless connection through cell phones
- Optical links through the air (called *free-space optics*)

Dial-up connections steadily increased in capacity from 300 bits per second in the early 1980s to a nominal 56 kilobits per second in the mid 1990s, when they reached the limits of standard telephone lines. These services were offered by companies called *Internet Service Providers* (ISPs) who used banks of modems to receive calls from customer modems making connections to the Internet. The earliest ISPs specialized in such connections and didn't operate other telecommunication services. This situation has changed over the years.

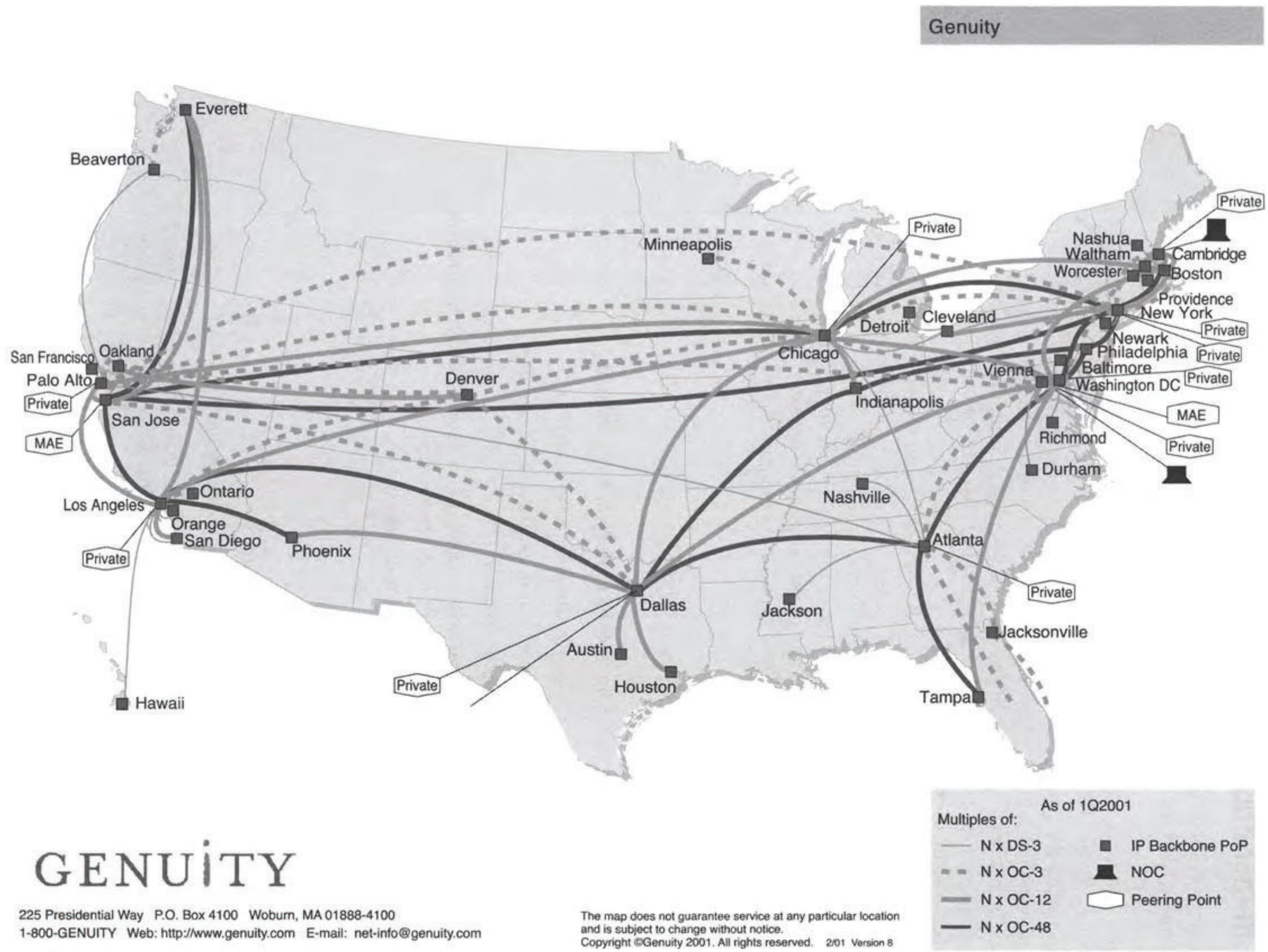


FIGURE 26.4
UUNet's Internet backbone in the United States. (Courtesy of UUNet)

The next step up is *broadband* service, which includes DSL, cable modems, fiber to the home, and some wireless connections. About half of all U.S. households with Internet access have broadband links. Broadband typically has downstream transmission of at least a few hundred kilobits per second. Fiber to the home has the greatest potential bandwidth. Broadband services were introduced by regional phone companies, cable television operators, and some competitive carriers. Local phone and cable networks provide most broadband services, although other companies may lease capacity to do so, depending on regulations.

Broadband includes DSL, cable modem, and fiber to the home.

Wireless Wi-Fi networks provide temporary connectivity at sites like Internet cafes, allowing roving users to connect to the Internet. Hotels, airports, and convention centers also offer Wi-Fi services, either for profit or as an enticement to attract customers for other services.

Individual users within organizations normally connect to the Internet through an organization-wide network. To understand how that works, let's look at the various levels of networking, starting from the user connection.

Local-Area Networks

Individual users connect to a *local-area network* or *LAN*, which links individual computers and other devices in an area. The definition of "local" can vary significantly. A household may operate its own local-area network when it connects a few computers and a printer to a router linked to a cable modem, as shown in Figure 26.5. Ethernet cables link the three computers and the printer to a home router, which allows the computers to share files and the printer. The router directs all signals to the proper place, connecting to the outside world through the cable. Wireless links could replace the cables from the router.

LANs link computers and other devices in a small area.

Office LANs typically have more equipment than home LANs. Figure 26.6 shows an office LAN serving a small work group. Five office computers and a more powerful workstation share

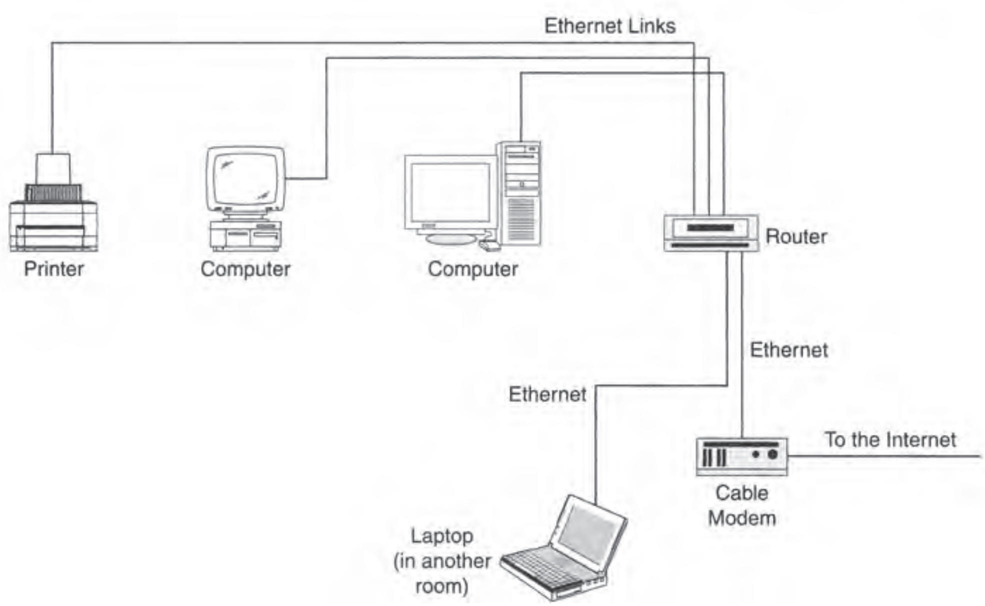
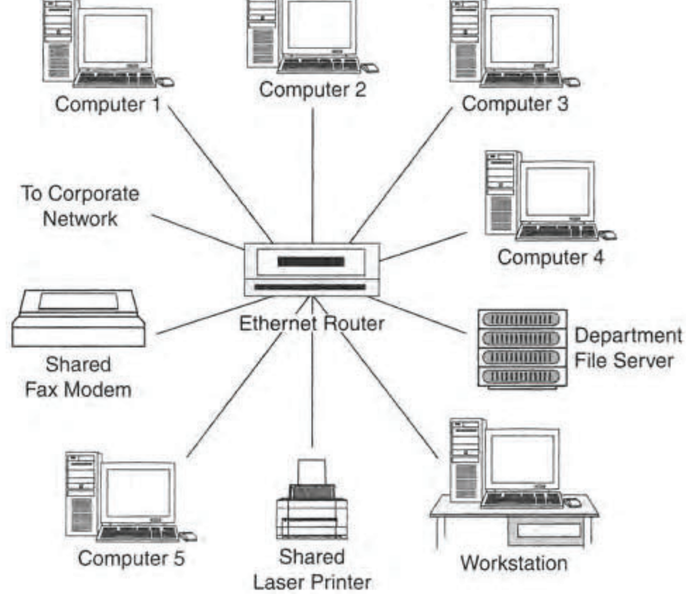


FIGURE 26.5
Home local-area network.

FIGURE 26.6
A LAN interconnects many devices that can send messages to each other and to external devices.



a laser printer and a fax modem. They also connect to a server, which holds master files of the group's projects. Connections are through an Ethernet router, which links to the company-wide network and the Internet.

LANs allow users to share files, data, and software.

Details vary widely, but in general LANs enable all devices to share software, files, and data. Signals can be transmitted through copper or fiber cables, or over wireless links. LANs generally can transmit two or more data streams at once, so the laptop user in the network of Figure 26.5 could surf the Internet while one of the desktop computers printed a file. (Actually, the two processes are not operating simultaneously, but switching back and forth so rapidly that users don't notice.)

LANs may have star, ring, or data-bus geometries.

Local-area networks have three configurations, as shown in Figure 26.7. In a star network, all signals pass through a central node, which may either actively retransmit or passively divide signals. Figures 26.5 and 26.6 show examples of active star Ethernet networks, in which the Ethernet router directs signals to other terminals like a telephone switch. A wireless Wi-Fi network similarly has a central base station, but it broadcasts all signals to all terminals within reach. In a ring network, the transmission medium connects all nodes, and signals can travel in both directions simultaneously (sometimes over two parallel paths for redundancy). In the data-bus topology, a common transmission medium connects all the nodes but does not form a loop, so the signal does not travel through all nodes in series. The ring, data-bus, and wireless star networks actually transmit all signals to all nodes, but the nodes ignore signals not addressed to them.

A local-area network can have many more users than the examples shown. Corporate networks seem to be local networks, but usually consist of a number of smaller department-scale networks linked together. These networks are sometimes called *corporate-area networks* or *campus-area networks.*

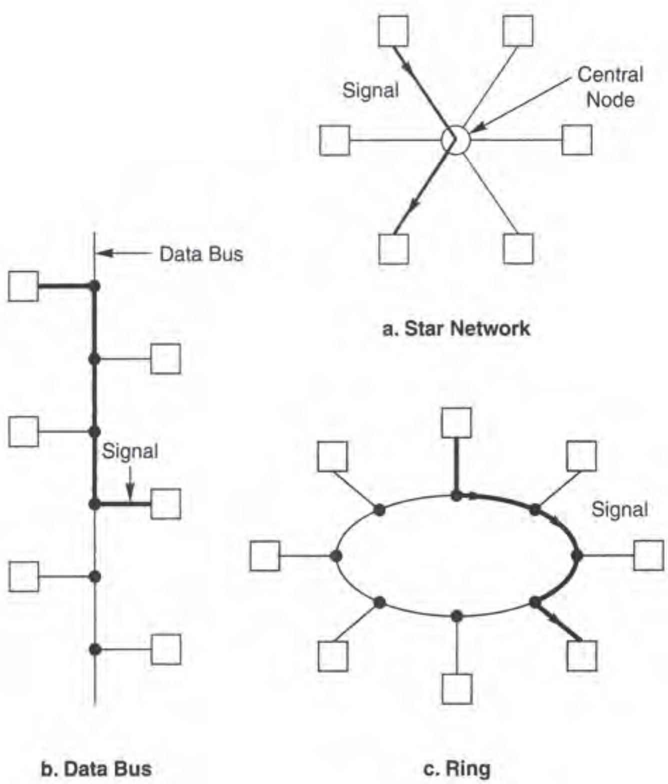


FIGURE 26.7
Star, bus, and ring LAN architectures.

Metro-Area and Wide-Area Networks

Private networks also can connect many separate locations in the same area, such as all the schools and municipal buildings in a city. These networks, called *metropolitan-area* or *wide-area networks,* interconnect other smaller networks, such as local-area networks.

Metropolitan-area networks connect separate locations.

The terms "metropolitan-area" and "wide-area" do not refer consistently to any specific geographic coverage. A metropolitan-area network (MAN) may serve the same area as a metro telephone network, or merely a few buildings on a corporate or college campus. A wide-area network may be a MAN, or it may be similar in scope to a regional or national network. You have to infer the geography from the context.

Desktop Data Transmission

A single personal computer and its peripheral devices may function as a desktop network. Some people attach many peripheral devices to their computers, such as printers, scanners, external backup devices, additional optical drives, external speakers, and fax modems. Generally these devices do not have Internet addresses, so they don't show up on the Internet. (Printers may have Internet addresses if they connect to a local area network through routers, but are visible only to users on the LAN.)

Data Transmission Technologies

So far I have said little about specific data transmission technologies beyond the brief introduction in Chapter 3. Now we'll learn some basic concepts of data networking and transmission. Data networking is a complex technology that can be implemented in different ways, so we'll only talk about common examples.

There are two basic types of data transmission: *data links*, which are point-to-point connections between two devices, and *networks*, which link three or more devices.

The primary emphasis here will be on networks because connectivity is important. However, many networks consist of many individual data links that collectively interconnect many devices. For example, a data link connects your computer to an external display screen, but when you connect the computer to a printer, a scanner, and an Internet server as well, you create a network.

Network Connections

The star, bus, and ring architectures for local-area networks, shown in Figure 26.7, are not the whole story. These three basic approaches can be implemented in different ways using different protocols.

Star networks can have active or passive hubs.

For example, a star network can be a passive system, where the central node is a passive optical star coupler of the type described in Chapter 14. Light from one terminal enters the star coupler, which divides it among all the output ports. However, this passive splitting consumes a lot of power, resulting in an attenuation of 10 dB for a 10-port coupler. In practice, star networks more commonly use active hubs, which can distribute signals by either switching or broadcasting them.

Switching requires a point-to-point connection between the active hub and each connected terminal. The hub receives input signals from terminal devices, then switches them to the destination terminal over the proper point-to-point link, usually a copper or fiber-optic cable. An Ethernet switch or router works like this, as shown in Figures 26.5 and 26.6.

Broadcasting distributes signals to all terminals.

Broadcast transmission sends signals to all terminals in the receiving area. This technique is used for wireless LANs, as shown in Figure 26.8. The base station receives wireless input signals, then broadcasts them to the local terminals. Only the target terminal for which a signal is intended can receive and decode the signal. A wireless LAN usually also has a connection to the Internet. The popular Wi-Fi system is an example.

A ring or data-bus network physically passes all data through the transmission medium, dropping parts of the signal at each terminal. The actual implementation varies. Signals can be dropped by using a passive coupler to split them, although the signal loses power at each node. The terminal then extracts the signals directed to it. Alternatively, each node can use an active coupler to decode the input signal, then retransmit it both to the attached terminal and to the next node.

Cable Transmission

Three main classes of cables are used in data connections: twisted copper wires, copper coaxial cable, and fiber.

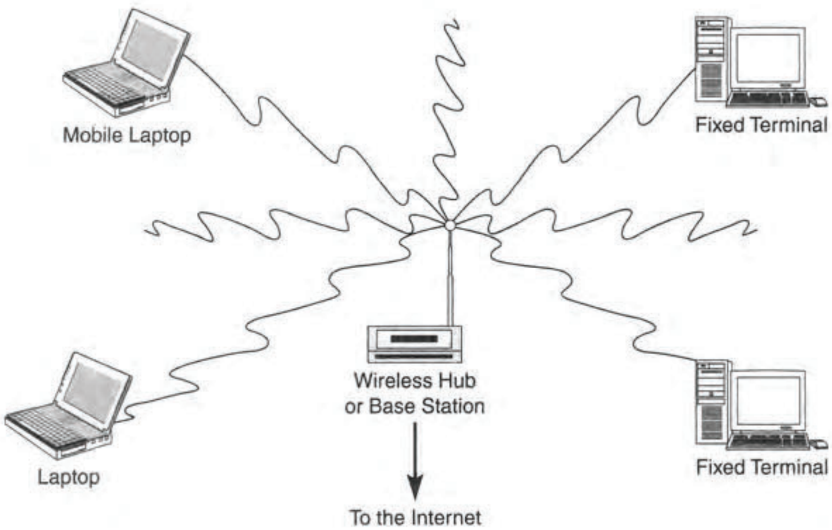


FIGURE 26.8
A wireless local-area network has an active central hub, which transmits signals to all terminals.

Twisted-wire pairs, which provide telephone and DSL service, have limited bandwidth. Special versions developed for data communications offer enhanced bandwidth. Figure 26.9 plots the loss per 100 m (*not* per km) versus signal frequency for four types of copper data-transmission cable. Categories 3 and 5 are unshielded twisted pairs meeting EIA/TIA standards. Shielded twisted pair is similar except the wire pairs are shielded by a metal foil

Category 5 cables use high-bandwidth twisted-wire pairs.

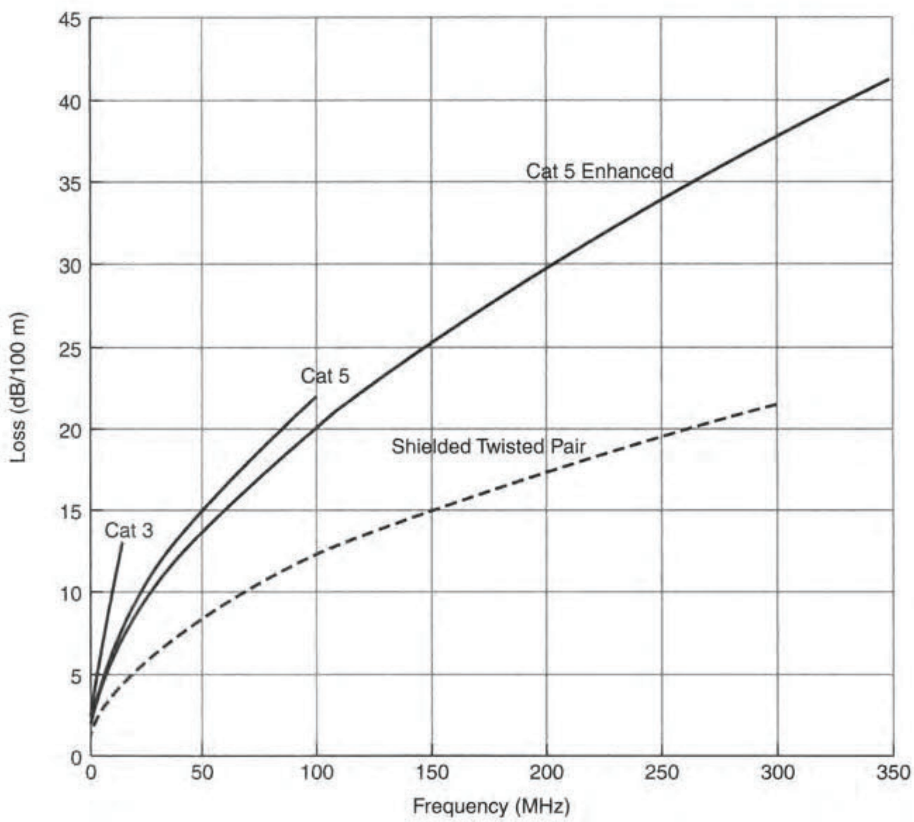


FIGURE 26.9
Typical loss of twisted-pair wiring designed for high-frequency use.

layer. Category 5 cable was developed for 100-Mbit/s fast Ethernet, and can carry signals up to 1 Gbit/s over the short distances of desktop connections. But as transmission distance and signal frequency increase, proper installation becomes critical.

Coaxial cable was used in many early data links and LANs, but few applications use it now because it is difficult to install. Coaxial cable is used for cable television systems that provide data service through cable modems.

Fiber offers much higher bandwidth and lower attenuation than either twisted-pair wiring or coaxial cable, and is used for fiber-to-the-home or fiber-to-the-premises systems. However, signals are generated in electronic form, so extra equipment is needed to convert electronic signals into optical form for transmission, then convert them back into electronic form for use at the receiving end. The extra cost is worthwhile if the signals are at high speed or must go long distances. But the cost is prohibitive for a link from your desktop computer to a cable modem—unless you have special requirements.

Fiber data links avoid electromagnetic interference, eavesdropping, and ground loops.

Because fibers carry signals as light rather than as electrical current, they avoid three types of problems that can occur when using copper: electromagnetic interference (EMI), vulnerability to eavesdropping, and undesired cable conductivity.

- *Electromagnetic interference* or *EMI* arises because long copper wires make good antennas, picking up signals radiating through the air. For example, the radio waves from a nearby strong AM radio station can induce electric current in telephone wiring, producing signals audible on the phone. Noise can also be induced in data communications by power lines running near equipment in locations such as elevator shafts or power substations.

- Just as radio signals can induce current variations in long copper wires, the variations in current flow as a signal is being transmitted cause the wires to emit radio waves. The emitted radio signals are faint, but can be detected with sensitive equipment. Eavesdropping is not a significant source of worry for most users, but it is for security agencies and financial organizations.

- Electronic designers assume that voltages vary relative to a common potential called the ground level. That's a reasonable assumption if the ground is a single metal chassis. But if a cable connects equipment in different buildings, that's a potential problem because semiconductor electronics are sensitive to variations of only a few volts. Differences in ground potential at the ends of a cable can generate current paths called *ground loops*, which produce noise. This problem is very common in electrical facilities. Voltage differentials also can generate sparks, which could cause explosions in oil refineries or chemical plants.

Because of these problems, fiber data links are used in special cases, even when copper cables could deliver the required bandwidth.

Wireless Transmission

There are several distinct types of wireless data transmission, ranging from wireless networks inside buildings to satellite data links. They both compete with fiber-optic systems and are part of the overall data network.

Wi-Fi is a wireless LAN for mobile computers.

Wi-Fi (for Wireless Fidelity) is the best-known example of wireless data transmission because it is widely used for personal computers. Wi-Fi is based on the IEEE (Institute of Electrical and Electronics Engineers) 802.11 family of standards and operates over short distances in the unlicensed radio bands at 900 MHz, 2.4 GHz, and 5 GHz. Wi-Fi networks have active hubs at their center, which can link to computers within 15 to 50 meters indoors, or somewhat longer distances outdoors. Another standard, called *Bluetooth*, allows lower-speed transmission over shorter distances with less expensive electronics. Both standards can connect with mobile devices.

Worldwide Interoperability for Microwave Access, or WiMAX, is a wireless metropolitan-area network design based on IEEE 802.16 standards. At this point, WiMAX covers a broad range of possible networks rather than a single specific network. The protocols allow operation at frequencies of 2 to 11 GHz or 10 to 66 GHz, and at the low end of that range high-power transmitters could reach 50 kilometers. However, most WiMAX networks probably will span no more than a few kilometers. Initially the active base station will transmit only to fixed terminals, but mobile terminals may be added later. WiMAX is intended to link Wi-Fi base stations to Internet servers and to distribute other data services.

WiMAX is a wireless metropolitan-area network.

Two other types of fixed wireless systems also can distribute data: *LMDS* (local multipoint distribution systems) and *MMDS* (multichannel multipoint distribution systems). LMDS base stations transmit up to 8 km in a line of sight in multiple bands between 28 and 31 GHz in the United States. LMDS is not widely used for its original application of distributing voice, video, and data services to homes, but it does provide wireless data links for businesses with a clear line of sight to the base station. MMDS operates at frequencies of 2.5 to 2.7 GHz, where a clear line of sight is not essential. However, its overall bandwidth is limited to 200 MHz, the equivalent of 33 6-MHz video channels, so it also is not widely used for home voice, video, and data service. MMDS is used for business data links, and has adequate range for rural signal distribution.

Satellites also can transmit data at high speeds, but their broad coverage areas make them more suitable for broadcasting than for point-to-point data transmission. Satellite data links to single users typically are limited to tens of kilobits per second—comparable to dial-up modems—and are expensive. Satellites are used mainly for connectivity in remote areas where other services are not available.

Satellites are better suited for broadcasting than for point-to-point links.

Microwaves also can be used for point-to-point data links. Systems direct microwaves in a narrow range of angles by using a dish antenna that is large relative to the wavelength. These systems can be used where cables are impractical or expensive to install, but generally require licenses from the FCC.

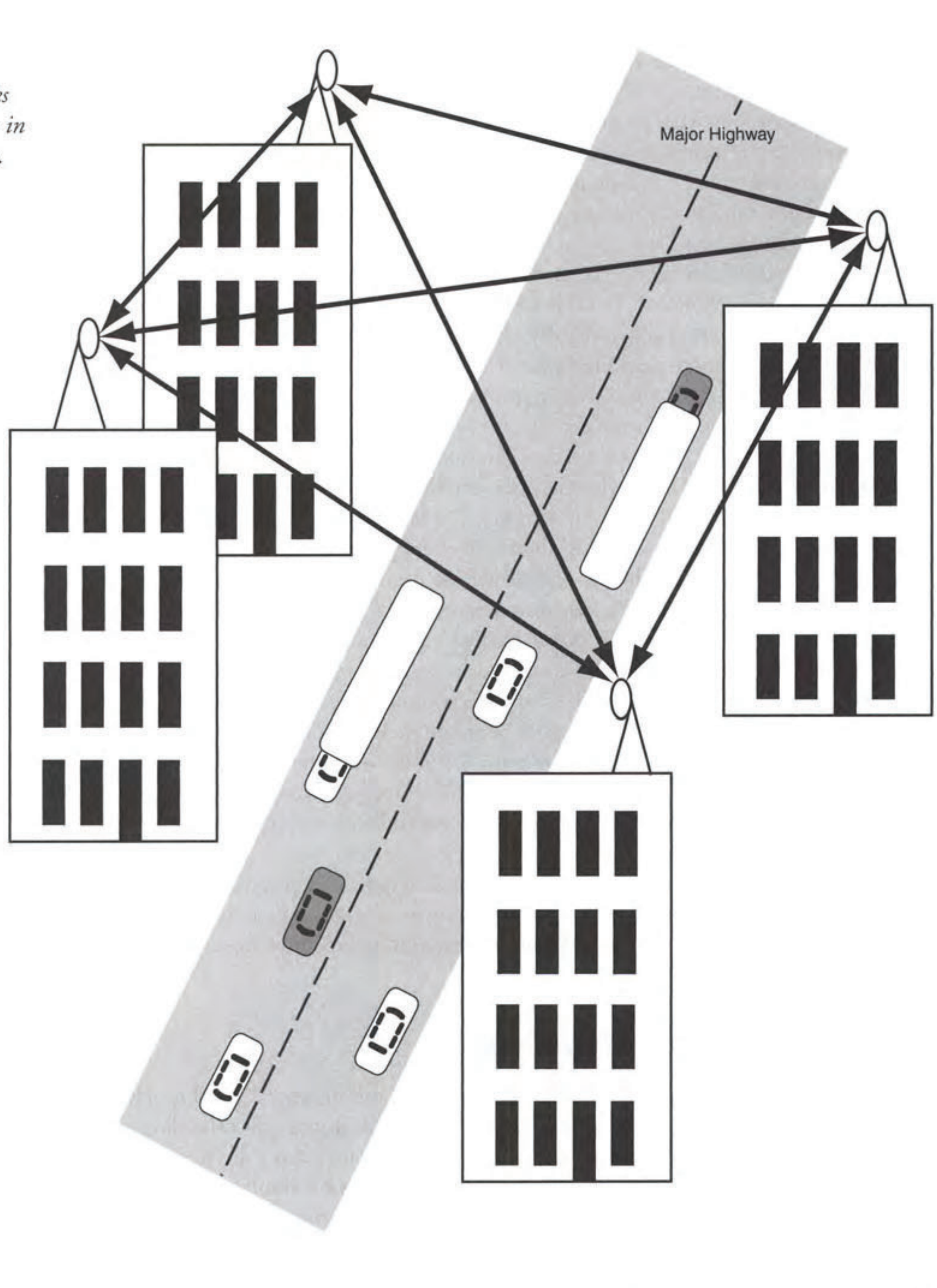
Free-space Optical Connections

Optical connections are wireless if the light goes through the air rather than through a fiber. The simplest examples are the remote controls used on televisions and other home entertainment equipment, which transmit coded infrared pulses over short distances using low-power LEDs. Higher data rates can be sent longer distances by aiming laser transmitters through the air. This technique is called *free-space optics* or *atmospheric optical transmission.*

Laser beams are normally tightly focused, so their output is concentrated in a small spot. But most laser links through open air spread the beam out to cover a larger area. This both avoids the potential eye hazard from a tightly focused laser beam and makes the light easier to pick up with an optical receiver. Even with this defocusing, laser beams remain highly directional, so they concentrate their output into a much narrower range of angles than a radio antenna. This makes free-space optics attractive for point-to-point communications.

Free-space optics transmit light between buildings.

FIGURE 26.10
Laser mesh links through the air in downtown area.



Air is not a reliable transmission medium because clouds, fog, or precipitation can block light, and haze scatters light over long distances. The attraction of free-space optics is that it avoids the cost of laying fiber. Point-to-point laser links can be combined to create a mesh among downtown buildings, as shown in Figure 26.10. The mesh architecture enables the links to continue transmitting signals even if one beam is temporarily blocked by a dense patch of fog or a passing pigeon. Typically individual links are only a few hundred meters.

Fiber Data-Link Design

The design examples in Chapter 21 and 22 were largely aimed at telecommunications applications. Data links and computer networks are generally much shorter, so coupling losses are more important than fiber attenuation.

Data links and local-area networks use graded-index *multimode* fibers, which now play little role in telecommunications. Although graded-index fibers are more expensive than step-index single-mode fibers, they can reduce the costs of transmitters, receivers, and connectors enough to justify their expense. Data links and LANs may even use step-index multimode fiber in certain cases. Dispersion does become an issue at high data rates, so most network standards have options for single-mode fibers, which rarely cause dispersion problems for data communications.

Multimode fibers are widely used in LANs and data links.

Data transmitters and transceivers often operate over specified span lengths of fiber, and are matched with receivers. Thus ratings are given in distance spanned rather than power level. Many data links also specify span losses of less than 10 dB, so they don't require bright transmitters.

Very-low-cost networks confined to single structures may use plastic fibers. Three configurations are possible:

Plastic fibers are used in short, low-speed data links.

- Step-index plastic fiber transmitting at 650 nm
- Graded-index plastic fiber transmitting in the visible light range
- Coarse-WDM over plastic fibers in the visible light range

Graded-index glass fibers are common in data networks, and many standards are built around them, as you will see in the next section. Graded-index fibers typically are used with laser or LED transmitters operating in the 850- and 1300-nm windows. Some standards include coarse-WDM in the 1300-nm window, but WDM is rarely used near 850 nm.

Single-mode fiber may be used at higher speeds or over longer distances. Single-mode fibers transmitting at 1300 or 1550 nm are fairly common in metropolitan-area networks and single links spanning more than a hundred meters. WDM is uncommon because it's often cheaper to lay another fiber than to set up the multiplexing and demultiplexing optics.

The acceptance of data link designs depends heavily on their use in industry standards.

Fiber in Standard Data Networks

Local-area networks such as the highly successful Ethernet family are based on industry-standard designs and interfaces. So are links between computers and peripherals. As transmission rates have increased, many of these standards have added options for fiber-optic transmission, although fibers are not widely used below data rates of 1 Gbit/s.

Fibers are not widely used in data networks below 1 Gbit/s.

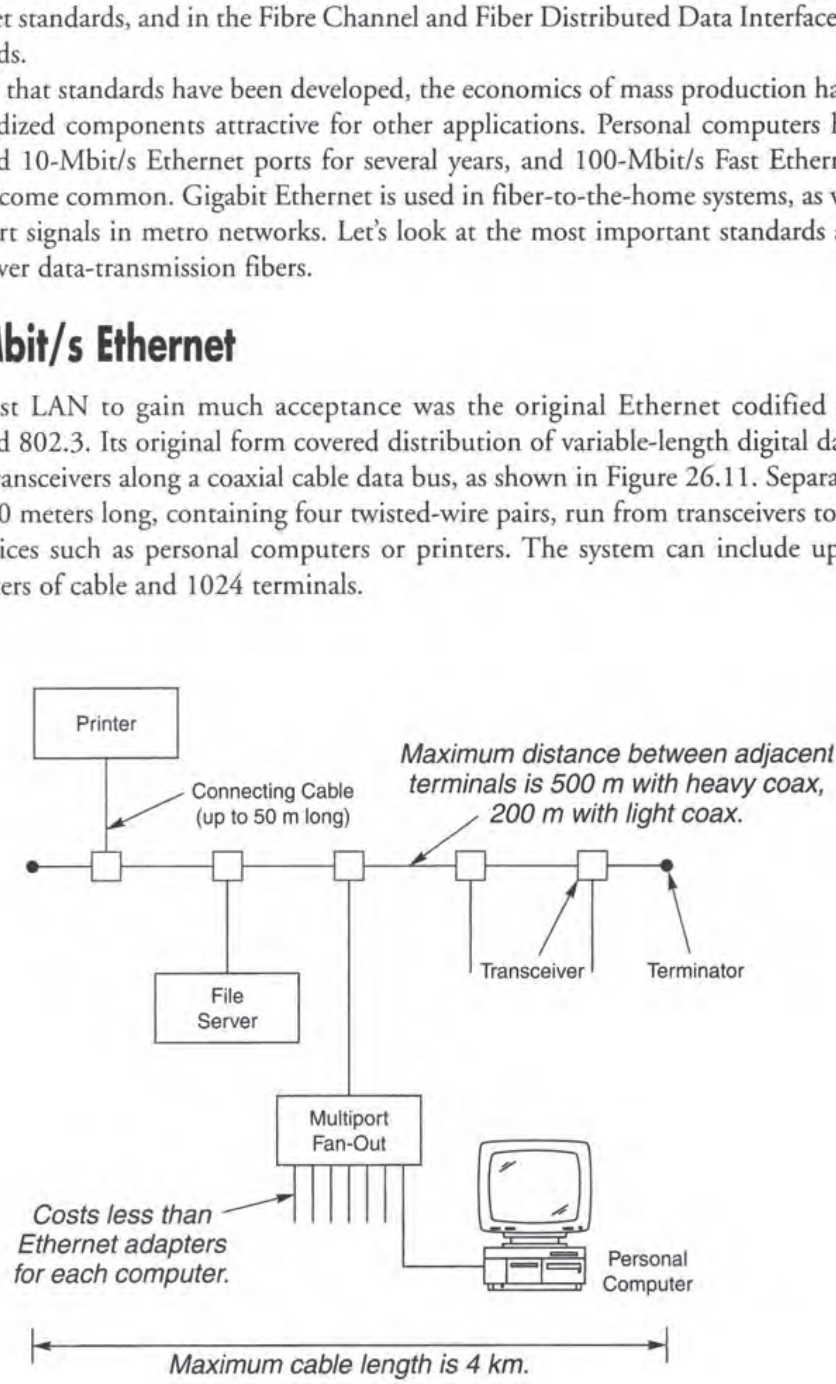
The growth in data rates has been steady. The first generation of local-area networks, such as the original Ethernet (10 BaseT) and the IBM Token Ring network, transmitted at about 10 Mbit/s. Higher-speed systems, originally developed to interconnect local-area networks within an organization, have been adopted for LANs as well. Fast Ethernet at 100 Mbit/s (100 BaseT) followed the original Ethernet. Gigabit Ethernet (1000 BaseX) followed in 1998, and later 10-Gigabit Ethernet. Fibers are important in the higher-speed Ethernet standards, and in the Fibre Channel and Fiber Distributed Data Interface (FDDI) standards.

Now that standards have been developed, the economics of mass production have made standardized components attractive for other applications. Personal computers have had standard 10-Mbit/s Ethernet ports for several years, and 100-Mbit/s Fast Ethernet ports have become common. Gigabit Ethernet is used in fiber-to-the-home systems, as well as to transport signals in metro networks. Let's look at the most important standards and how they cover data-transmission fibers.

10-Mbit/s Ethernet

The first LAN to gain much acceptance was the original Ethernet codified as IEEE standard 802.3. Its original form covered distribution of variable-length digital data packets to transceivers along a coaxial cable data bus, as shown in Figure 26.11. Separate cables up to 50 meters long, containing four twisted-wire pairs, run from transceivers to individual devices such as personal computers or printers. The system can include up to four kilometers of cable and 1024 terminals.

FIGURE 26.11 *Original elements of 10-Mbit/s Ethernet.*



Ethernet networks have no overall controller; transceivers share control functions. If a terminal is ready to transmit a signal, its transceiver checks to see if the data bus is transmitting another signal, and waits if it detects one. If the data bus is free, the terminal starts transmitting and continues until it either finishes or detects data transmitted simultaneously by another terminal (an event called a *data collision*). Data collisions occur because signals take time to travel through the data bus. If signal velocity is 1 meter every 6 nanoseconds, a collision can occur if two terminals 300 m apart start transmitting within 1.8 μs of each other. If a terminal detects a collision, it waits a random interval before trying again.

Ethernet has changed over the years. Lighter coaxial cables or twisted wire pairs can replace the original heavy coax data bus, although this reduces the cable's maximum span. Routers or switches that serve as active hubs in a star-geometry network, like the ones shown in Figures 26.5 and 26.6, can replace simple transceivers.

Fiber can extend the range of 10-Mbit/s Ethernet.

Optical fibers can stretch transmission beyond the limit imposed by the attenuation of coaxial cable to the one imposed by signal transmission time through the network. For example, a fiber cable might extend to a remote terminal in a separate building, beyond the limit of copper cables. The limit depends on whether the network operates in *full-duplex mode*, in which terminals transmit and receive simultaneously, or *half-duplex mode*, in which terminals can do only one thing at a time. In half-duplex mode, either single-mode or multimode fiber can transmit up to 2 km; in full-duplex mode, multimode fiber can transmit up to 2.5 km between terminals, and single-mode can span up to 15 km.

Fast Ethernet (100 Mbit/s)

Fast Ethernet (100 BaseT) is a faster version of the original Ethernet. It retains the frame format and transmission protocols of the original 10-Mbit/s Ethernet, but uses interface cards that operate at 100 Mbit/s. Fast Ethernet uses the same cables, but the faster speed limits the maximum runs on coax or Category 5 cable to 100 m.

Fiber can extend Fast Ethernet spans beyond 100 m.

The fiber-optic version, called 100Base-FX, allows half-duplex transmission to 412 meters, and full-duplex transmission to 2 km for multimode fiber and 10 km for single-mode fiber. Loss is limited to 11 dB per fiber span, including connector loss.

In practice, copper is used for most Ethernet and Fast Ethernet links.

Gigabit Ethernet (1 Gbit/s)

The next step is Gigabit Ethernet, which as you might expect operates at 1 Gbit/s. This standard uses the same protocols and frame format as slower Ethernets, but with only full-duplex transmission. Because of the high speed, Gigabit Ethernet node spacing is shorter. A special cable called *twinax*—a coaxlike cable with a shielded twisted pair at the center instead of a single metal wire—is used for jumper cables to 25 m (1000BaseCX). Splitting the 1 Gbit/s among the four twisted-wire pairs in a Category 5 cable allows it to span distances to 100 m (1000BaseT).

Gigabit Ethernet needs fiber to transmit beyond 100 m.

Fiber allows longer transmission distances, and is considered the backbone for Gigabit Ethernet. The standard terminology distinguishes only between 850-nm short-wavelength transmission (1000BaseSX) and 1300-nm long-wavelength systems (1000BaseLX), but

Table 26.1 Fiber transmission formats for Gigabit Ethernet

Transceiver	Fiber Types	Bandwidth (MHz-km)	Maximum Range (m)
850-nm laser	62.5/125	160	220
850-nm laser	62.5/125	200	275
850-nm laser	50/125	400	500
850-nm laser	50/125	500	550
1300-nm laser	62.5/125	500	550
1300-nm laser	50/125	400	550
1300-nm laser	50/125	500	550
1300-nm laser (1000Base-LX)	9/125 (single-mode)	—	5000
1300-nm long-haul laser (1000Base-LH)	9/125	—	50,000 (50 km)
1550-nm long-haul laser (1000Base-LH)	9/125	—	100,000 (100 km)

more fiber and wavelength combinations are possible, as listed in Table 26.2. Note that the bandwidth specifications show two grades of both 50/125 and 62.5/125 graded-index fiber.

Gigabit Ethernet includes several types of fiber links.

Two factors limit transmission distances: fiber dispersion and transmitter power. Fiber dispersion dominates for multimode graded-index fibers. Attenuation limits transmission distance for single-mode fibers. Transceivers using high-power lasers at 1310 or 1550 nm (1000BaseLH) can span much greater distances than the nominal 5 km of 1000BaseLX, but not all such transceivers can reach the distance limits shown in Table 26.1. These long-haul transceivers are used mainly in metro networks, and the receiver end must not be overloaded with excess laser power.

The Gigabit Ethernet standard is derived from the Fibre Channel specification for 1-Gbit/s transmission, so the two standards share many features.

10-Gigabit Ethernet

10-Gbit/s Ethernet is mainly for MANs and WANs.

The next logical step was to 10-Gigabit Ethernet. This standard was approved by IEEE in 2003 and was designed largely for metropolitan-area networks to provide backbone links between other networks. It also will provide relatively short connections between high-speed equipment in the same building. The transmission format is compatible with the 10-Gbit/s OC-192 SONET rate, so a 10-Gigabit Ethernet output could drive one optical channel in a DWDM system at 10 Gbit/s for long-haul transmission.

Copper can carry 10-Gbit/s signals only over very short distances, so the 10-Gigabit Ethernet standard concentrates on fiber. Table 26.2 shows recommended fiber

Table 26.2 Fiber transmission distances for 10-Gigabit Ethernet

Type	Transmitter and Channels	Fiber Types	Fiber Bandwidth	Distance Limit
10Gbase-S	850 nm, 1	62.5/125 graded-index	160 MHz-km	26 m
10Gbase-S	850 nm, 1	62.5/125 graded-index	200 MHz-km	33 m
10Gbase-S	850 nm, 1	50/125 graded-index	400 MHz-km	66 m
10Gbase-S	850 nm, 1	50/125 graded-index	500 MHz-km	82 m
10Gbase-S	850 nm, 1	50/125 graded-index	2000 MHz-km	300 m
10Gbase-LX4	1300 nm, 4 CWDM	62.5/125 graded-index	500 MHz-km	300 m
10Gbase-LX4	1300 nm, 4 CWDM	50/125 graded-index	400 MHz-km	240 m
10Gbase-LX4	1300 nm, 4 CWDM	50/125 graded-index	500 MHz-km	300 m
10Gbase-LX4	1300 nm, 4 CWDM	9/125 single-mode	—	10 km
10Gbase-L	1300 nm, 1	9/125 single-mode	—	10 km
10Gbase-E	1550 nm, 1	9/125 single-mode	—	40 km

transmission formats, including short links over multimode fiber, coarse-WDM with four 2.5-Gbit/s channels, and single-channel transmission at 10 Gbit/s.

As with Gigabit Ethernet, the high chromatic dispersion of graded-index fiber imposes transmission distance limits on 10-Gigabit Ethernet, particularly at 850 nm. The nominal link power budgets are only 7.3 dB, so the transmitters use low-power VCSELs. Power budgets are only slightly higher in the four-channel CWDM transmitters operating at 1310 nm in graded-index fiber. Much longer transmission distances are possible using single-mode fibers, where the limit comes from laser power, not dispersion.

Chromatic dispersion limits span length for graded-index fiber.

Fibre Channel

The *Fibre Channel* standard was developed for use in computer systems and networks, particularly in *storage-area networks*, which link computers and peripherals used for data storage. Such networks transmit data at high speeds over various distances (whether across a room or across the state). Large financial institutions and corporations usually keep copies of their financial records off-site, backing up their main data banks to remote server farms in case of a catastrophe at headquarters. Figure 26.12 shows the organization of such systems, with back-office servers providing the interface between the storage-area network and the local-area network that serves individual computers in a large company.

Fibre Channel links computers with data storage equipment.

Fibre Channel also can be used for backbone networks and switched transmission. Hubs connect nodes to form loops; switches connect to make a fabric that directs signals between

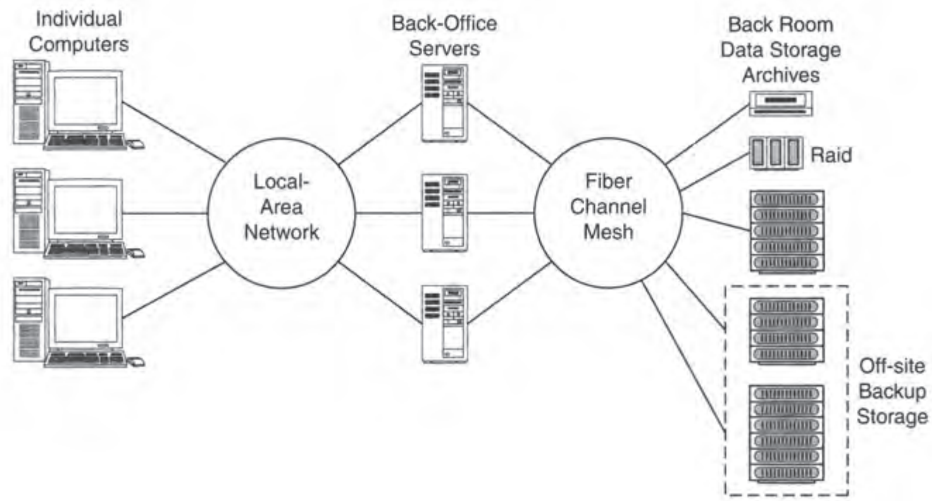


FIGURE 26.12 *A storage-area network includes local and remote data storage.*

devices somewhat like the phone system. It is designed to operate on scales from the backplane of a computer (less than a meter) to a metropolitan-area network larger than five kilometers.

Table 26.3 lists Fibre Channel data rates for current and planned standards. The data rates reflect computer-industry practices, which count data in eight-bit bytes rather than in bits. The bit rate column lists the equivalent data rate in bits per second, not counting error-checking and correction bits.

As mentioned earlier, some of the physical standards for Gigabit Ethernet data transmission were based on Fibre Channel standards, and higher-speed Ethernet standards also draw on ideas from Fibre Channel. Like Gigabit Ethernet, Fibre Channel includes provisions to transmit on copper as well as on fiber, and uses different fiber transmission windows. The Fibre Channel protocol also defines the number of terminals in a loop and the arrangement of hubs and switches. We won't cover the details because they are beyond the scope of this book.

Fiber Distributed Data Interface (FDDI)

FDDI is a 100-Mbit/s token-ring network.

The *Fiber Distributed Data Interface* (FDDI) network is a ring network. As shown in Figure 26.13, two rings transmit signals in opposite directions to a series of nodes at 100 Mbit/s. The standard also specifies concentrator-type terminals that allow stars or branching trees

Table 26.3 Fibre Channel speeds

Designation	Data Rate	Bit Rate (no overhead)
1GFC	200 megabytes/sec	1.6 Gbit/s
2GFC	400 megabytes/sec	3.2 Gbit/s
4GFC	800 megabytes/sec	6.4 Gbit/s
8GFC	1600 megabytes/sec	12.8 Gbit/s
10GFC	2400 megabytes/sec	19.2 Gbit/s

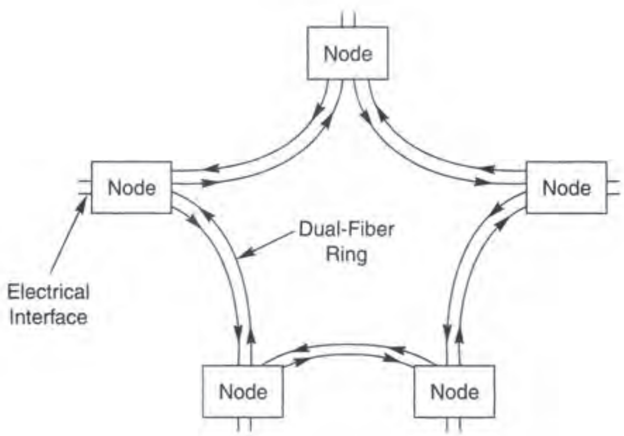


FIGURE 26.13
FDDI dual-fiber ring.

to be added to the main FDDI backbone ring. Normally one ring carries signals while the other is a backup in case of component or cable failure. The maximum distance between nodes is 2 km over multimode fiber at 1300 nm.

FDDI transmission uses the "token passing" scheme used in slower token-ring networks covered by the IEEE 802.5 standard. Terminals do not contend for slots to send signals, as in Ethernet, but instead pass an authorization code called a *token* around the ring, which travels through each node in sequence. When the token reaches a node that is ready to send a message, the node holds the token and sends the message, which is cancelled after it loops around the ring. Then the terminal that sent the message passes the token around the ring again. This is a more orderly protocol than Ethernet, but it has limitations.

FDDI was developed for fiber-optic transmission, but a copper version sometimes called CDDI, has been developed for short-distance applications.

Other Data Communications Standards

Other data communications standards also cover fiber-optic data links and networks, and more are in development. Some cover specific applications such as automotive or aerospace systems. Others modify existing standards to include provisions for fiber. New standards are also in development. These include high-speed protocols, such as 40-Gigabit Ethernet, which seemed like a good idea during the telecommunications bubble but are no longer an urgent priority. We won't cover these standards, but you should remember that they do exist.

What Have You Learned?

1. Early local-area networks linked dumb terminals to mainframe computers. The Internet grew from links between local-area networks.
2. Computer data transmission comes in bursts, which are processed using packet switching.

3. Computer networking standards are structured in layers, like other telecommunication standards.
4. The Internet backbone system links Points of Presence (POPs), which are comparable to the major switching nodes on the long-distance telecommunications network.
5. Homes connect to the Internet through dial-up modems or broadband connections. Broadband includes DSL, cable modem, fiber to the home, and some types of wireless systems. Businesses connect through local-area networks and metropolitan-area networks.
6. Local-area networks (LANs) link individual computers and other devices within the same building. Metropolitan-area networks interconnect LANs at separate locations.
7. Computers exchange data over point-to-point links between pairs of devices or through LANs. Common LAN configurations are the star, ring, and bus. Star networks can have active or passive hubs.
8. Copper wires are cheap for data transmission, but they cannot carry signals as far or as fast as fibers. Fibers offer room for potential expansion of services.
9. Category 5 cables are twisted-pair cables with high bandwidth (for copper).
10. Fibers are immune to electromagnetic interference. Fibers do not radiate electromagnetic fields, making data transmission on fiber more secure than on copper.
11. Wireless networks include the Wi-Fi local area network and the WiMAX metropolitan area network.
12. In free-space optics, laser beam links transmit data through the air between pairs of points. Many such links can form a mesh network to connect buildings without the cost of laying cable.
13. Multimode graded-index fibers are widely used for local-area networks and short data links because they allow the use of inexpensive transceivers. Single-mode fiber is needed for distances beyond about 100 meters at 1 Gbit/s. Plastic fiber is used only in very short data links and networks operating at low speeds.
14. Local-area networks, such as the highly successful Ethernet family, are based on industry-standard designs and interfaces.
15. The original Ethernet transmitted 10 Mbit/s. Fast Ethernet transmits at 100 Mbit/s, Gigabit Ethernet at 1 Gbit/s, and 10-Gigabit Ethernet at 10 Gbit/s. The faster standards rely heavily on fiber transmission. Gigabit Ethernet uses components developed for Fibre Channel.
16. Fibre Channel includes point-to-point, loop, and switched transmission for storage-area networks that link computers with data-storage peripherals.

What's Next?

In Chapter 27, I will cover fiber-optic video transmission, with particular emphasis on cable-television networks.

Further Reading

Fibre Channel Association: *http://www.fibrechannel.com/*

Joseph H. Levy and Glenn Hartwig, *Networking Fundamentals*, 2nd ed. (IDG Books, Foster City, CA, 1998)

Peter Rybaczyk, *Novell's Internet Plumbing Handbook* (Novell Press/IDG Books, San Jose, CA, 1998)

Charles Spurgeon, *Ethernet: The Definitive Guide* (O'Reilly and Associates, 2000)

10-Gigabit Ethernet Alliance: *http://www.10gea.org/*

Questions to Think About

1. If the Internet is the computer equivalent of the long-distance backbone system for telephony, what is a good analogy for the regional telecommunications network?
2. Your cable modem shares a loop of cable with other subscribers in your neighborhood. This in effect connects all of you to a local area network run by the cable company. Suppose that the modem delivers 10 Mbit/s to your computer's Ethernet port if nobody else is online. Nine of your neighbors subscribe after you say how great the service is. If the capacity available to you depends only on the number of users, how much of the original capacity is left?
3. A free-space optical network can transmit signals between any two office buildings 95% of the time on foggy days. If you have a single laser link to your building, how much time would you expect to be down during a 24-hour interval of foggy weather? Suppose you could add two more completely independent laser links that would connect you to the same network. How much would your service improve?
4. Your company has just signed a 10-year lease on a renovated building. Your old building had a standard 10-Mbit/s Ethernet, but traffic was doubling every year and the network is now at capacity. You want to stay with Ethernet standards. How long can you use Fast Ethernet before you run out of capacity? How long can you use Gigabit Ethernet?
5. You need to transmit Gigabit Ethernet between a pair of buildings 400 meters apart. What are your options? What are your options if you upgrade to 10-Gigabit Ethernet?
6. Why would you not use DWDM to increase transmission capacity of a local-area network?

Chapter Quiz

1. Points of Presence (POPs) on the Internet are

a. phone numbers called by dial-up modems.

b. addresses of Web sites.

c. major nodes where Internet backbone systems transfer signals.

d. long-distance data transmission lines.

e. computers with Internet access.

2. Data flow to and from computers

a. varies over time in a regular and predictable way.

b. occurs in irregular bursts.

c. is at a constant speed determined by your modem.

d. is at a constant speed determined by your computer.

e. is at a constant speed from your computer but incoming data rates can vary.

3. Which of the following is a local-area network (LAN)?

a. a system that interconnects many nodes by sending all signals through a central passive node

b. a system that connects many nodes by sending all signals through a central active node

c. a ring network with a transmission medium that passes through all nodes

d. a common data bus that connects all nodes but does not form a complete ring

e. all of the above

4. Why are optical fibers immune to EMI?

a. They transmit signals as light rather than as electric current.

b. They are too small for magnetic fields to induce currents in them.

c. Magnetic fields cannot penetrate the glass of the fiber.

d. They are shielded by the outer conductors in the cable.

5. The main reason optical fibers are not used for short point-to-point links is because

a. they require switches to direct signals.

b. they need expensive optical transmitters and receivers to convert electronic signals into optical form.

c. fiber cannot provide electrical grounding.

d. fiber does not operate properly at low data rates.

e. fiber is difficult to upgrade.

6. Broadband connections do *not* include

a. DSL.

b. cable modems.

   c. dial-up modems.
   d. fixed wireless links.

7. What kind of local area network is Wi-Fi?
   a. passive star
   b. active star
   c. data bus
   d. ring

8. When would optical fibers be used in standard (10-Mbit/s) Ethernet?
   a. Never. The standard requires coaxial cable.
   b. to extend transmission distance to reach remote terminals
   c. All Ethernet standards require fiber for distances beyond 10 m.
   d. when the network includes an active hub
   e. when the stockroom is out of coaxial cable

9. When would optical fibers be used in Gigabit Ethernet?
   a. Never. The standard requires coaxial cable.
   b. Always. The standard is specified only for optical fiber.
   c. beyond short distances in most cases
   d. only when Gigabit Ethernet must be connected to an FDDI network
   e. only when connecting to the Internet

10. What wavelength(s) is/are used in graded-index fiber for Gigabit Ethernet?
   a. 650 nm
   b. 650 and 850 nm
   c. 650, 850, and 1300 nm
   d. 850 and 1300 nm
   e. 850, 1300, and 1550 nm.

11. Which standard was developed to link servers with data storage systems?
   a. Ethernet
   b. Fast Ethernet
   c. Gigabit Ethernet
   d. FDDI
   e. Fibre Channel

12. At what distances could graded-index fibers be used in 10-Gigabit Ethernet?
   a. only for distances less than 50 m
   b. for distances up to 300 m
   c. for distances up to 1 km

d. for distances up to 10 km

e. for distances greater than 300 m

13. What type of fiber has the shortest range for 10-Gigabit Ethernet?

a. 9/125 single-mode fiber transmitting one wavelength at 1300 nm

b. 50/125 multimode fiber transmitting four wavelengths at 1300 nm

c. 50/125 multimode fiber transmitting 850 nm

d. 62.5/125 multimode fiber transmitting 850 nm

e. 62.5/125 multimode fiber transmitting four wavelengths at 1300 nm

14. What is the primary limit on the transmission distance in Question 13?

a. chromatic dispersion

b. attenuation in the fiber

c. attenuation in the WDM optics

d. low-power light source

e. all of the above

CHAPTER

27

Video Transmission

About This Chapter

Cable television networks have long used fiber optics to distribute signals partway to homes, reaching neighborhood nodes that distribute signals through coaxial cables to individual homes. As you learned in Chapter 25, cable systems are converging with local phone systems, with both expanding to offer voice, video, and data services. Cable networks also are shifting to digital television.

This chapter explains the basics of video systems and transmission, covering both today's analog video technology and the new digital television standard. It explains how cable systems operate, how they use fiber technology, and how they are adapting the new digital technology. A final section describes other video applications of fiber.

Video Basics

Video signals encode changing images, usually in color, and usually include sound. Because the images are changing, new pictures must be transmitted continuously, so the human eye can see the changes. This requires more bandwidth than audio signals, and makes video signals considerably more complex. The details depend on the technology used to display the image and on the signal format.

Analog television is raster scanned.

Traditional analog television breaks the image into a series of parallel horizontal lines, a process called *raster scanning*. You can see the lines best if you look at an old analog black-and-white television with a cathode-ray-tube (CRT) screen. The color and brightness vary continuously along the length of each line, and your eye blends the lines into a composite image. Figure 27.1 shows how raster scanning represents a simple black-and-white picture, with the thin raster lines left in the background to show how they build the image.

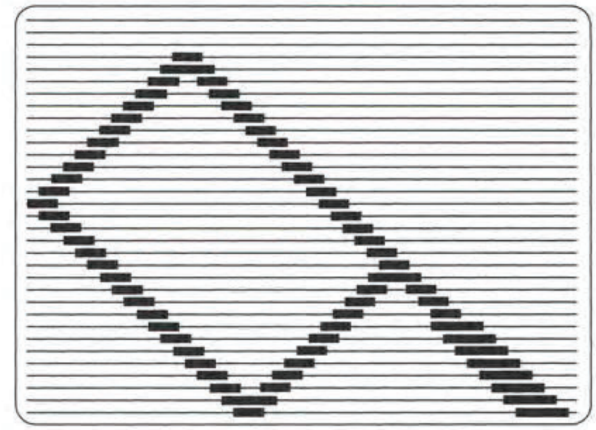


FIGURE 27.1
Raster scanned image is made from many parallel lines.

Digital television displays patterns of dots.

Digital television breaks the image into a pattern of dots arranged in straight lines across the screen. You can see this pattern if you look at your screen through a magnifier. Each line of dots is equivalent to a raster-scan line on a CRT analog television. If fact, in a newer color set, the lines break down into an array of dots when magnified.

On a color screen, each "point" of white light actually is an array of three colored spots—red, blue, and green—which together look white to the eye. This color information is included in both analog and digital signals. Changing the relative brightness of the three colored picture elements or *pixels* generates many intermediate colors.

Frame rate is the number of images shown per second.

The *frame rate* is the number of new images shown each second. Flashing these images sequentially gives the illusion of motion, although each frame is actually a still picture. The standard frame rate for motion picture film is 24 frames per second; for analog television it's 30 frames per second. These rates are fast enough that the eye does not see the flicker of changing pictures.

Resolution measures the number of lines or pixels on the screen. The more lines, the better the picture quality and the more detail visible to the eye.

Video Transmission Requirements

Video requires much more transmission capacity than sound or text.

Video transmission requires much more transmission capacity than sound or text files. It's often said that one picture is worth a thousand words, but Table 27.1 shows that a picture requires considerably more transmission capacity than a 1000-word text file. It also shows that bandwidth requirements increase with the resolution, although it is hard to compare digital and analog bandwidths.

The bandwidth required to transmit raw digital *high-definition television* (HDTV) is 1.5 Gbit/s, a staggering amount considering the number of video channels that have to be transmitted. Fortunately digital technology can reduce the bandwidth requirements by comparing sequential frames. If you step through individual frames on a DVD player or videotape, you can see that the picture displayed usually doesn't change too much from frame to frame. Digital processors can compare successive frames and throw away the parts that are unchanged, transmitting only the changes. Some losses are inevitable, but

Table 27.1 Comparison of approximate video, voice, and text transmission requirements

Transmission	Analog Equivalent	Digital Equivalent (No Compression)	Digital Equivalent (Compressed)
Standard U.S. analog television (NTSC)	6 MHz	270 Mbit/s	2–10 Mbit/s
HDTV (U.S. format)	~100 MHz	1.5 Gbit/s	19.3 Mbit/s
Voice telephone	3 kHz	64 kbit/s	~10 kbit/s
One standard TV video frame		9 Mbits	
One HDTV video frame (1/60 s)		25 Mbits	
1000 spoken words (5 min on phone)		20 Mbits	
1000-word text file		60 kbits	

usually they aren't significant; and *compression* reduces the data rate down to 19.3 Mbit/s, which is far more manageable.

The artifacts from digital compression are visible when data rates are squeezed even further for Web casting to broadband Internet links at 150 kbit/s or 300 kbit/s. The picture occupies only a small part of your screen, and objects in the picture get lost if they move too fast on the screen.

Transmission Standards

Video is transmitted in standardized formats.

Video signals are transmitted in standardized formats so transmitters can talk to receivers. These formats have evolved for historical reasons and are often not ideal. One difference in analog video formats is the number of frames per second, originally chosen to be half the frequency for alternating current (60 Hz in North America and 50 Hz in Europe). The North American standard for analog broadcast color television was chosen in the 1950s to be compatible with older black-and-white receivers because broadcasters did not want to lose that audience.

New standards have been developed for digital television. The original goal was higher screen resolution, or *HDTV*, for large screens, but the standards were broadened to cover *advanced television* (ATV), for sets with smaller screens. The technology comes in part from high-resolution computer monitors. Importantly, the digital standard signals are *not* compatible with existing analog television sets, which will require adapters when television broadcasts shift completely to digital television.

Other video standards are in use, such as those for computer monitors, but I will concentrate on television standards.

Standard Broadcast Analog Video

NTSC video displays 30 analog 525-line frames a second.

The present analog standard for broadcast television programs in North America is the *NTSC* format, from the National Television System Committee. The analog signals carry information representing the lines that compose the screen images. Pictures are displayed as 525-line frames (although a few lines do not actually show up on the screen). Nominally, NTSC shows 30 frames a second, but to keep the image from flickering to the eye, NTSC uses an interlaced scanning technique. First it scans odd lines on the display, then the even lines, then the odd lines again, as shown in Figure 27.2. Technically, this interlaced scan displays 60 half-images (called fields) a second, with only 267 lines of resolution each, but this fools the eye, giving the appearance of high resolution while avoiding the flicker of slower scanning speeds.

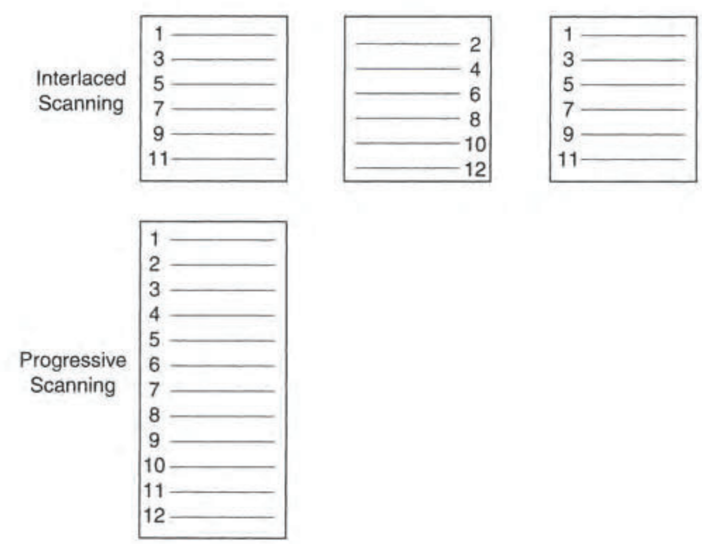
Nominally, the NTSC video bandwidth is 4.2 MHz, with the sound carrier at a higher frequency. However, for broadcast the video signal is used to modulate a radio-frequency signal, a process that increases overall bandwidth to 6 MHz, which is the amount of radio-frequency spectrum allocated to each broadcast television channel in the United States. Figure 27.3 shows the structure of this signal, which extends from 1.25 MHz below the carrier frequency to 4.75 MHz above the carrier. The NTSC format is used in North America, Japan, Korea, the Philippines, and much of South America.

PAL and SECAM are interlaced scanning systems showing 25 frames of 625 lines each per second.

Two other broadcast television standards are in wide use: PAL and SECAM. Both are interlaced scanning systems that show 25 frames (50 fields) per second, each frame with 625 lines. These have nominal video bandwidth of 5 to 6 MHz and broadcast channel bandwidth of about 8 MHz. PAL and SECAM systems are used in Europe, mainland Asia, Africa, and parts of South America.

These standards were set for television broadcasting from ground-based transmitters. National and international standards set aside specific frequencies for television broadcasting, with each channel allocated the required bandwidth (6 MHz for NTSC channels).

FIGURE 27.2
Interlaced and progressive scanning.



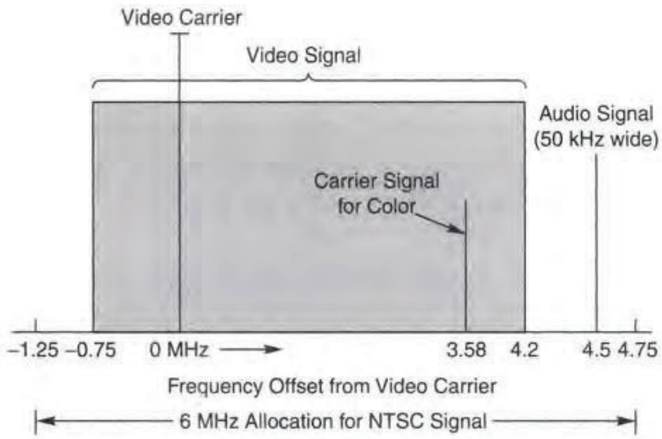


FIGURE 27.3
Structure of NTSC broadcast video signal.

These standards have come into wide use for other types of video because NTSC, PAL, and SECAM equipment is readily available.

Broadcast video standards were established decades ago, when color television came on the market. (The NTSC standard was a modified version of the original North American standard for black-and-white television, which goes back to 1948.) This means that these standards were developed for the vacuum-tube technology available in the electronic stone age.

Standard video formats are decades old.

Computer Displays and Video Formats

It might seem logical to use standard television displays for computers, but the two technologies are not readily compatible. Television sets are adequate displays for many computer-based video games, and sufficed for some early personal computers. However, text displayed on a screen with interlaced scanning does not show up well because the interlacing effectively mixes information from successive frames. The best displays for computers use progressive scanning in which all lines are scanned one at a time, then the entire screen is rescanned, as shown in Figure 27.2.

Computer displays require progressive scanning to show text clearly, not NTSC format.

Progressive scanning demands more bandwidth and faster electronics than interlaced scanning—because it transmits 60 (or sometimes more) complete frames a second to avoid flicker. NTSC video transmits 60 interlaced half-frames or fields, so its resolution is lower.

Multimedia or interactive video displays are hybrids, based on a combination of computer and television technologies. They don't have their own special display standards; those that play on computers use computer formats, those played on television sets use television formats. The American HDTV standard allows both progressive and interlaced scanning.

Several different technologies are used for displays. Until several years ago, virtually all desktop computers and television sets used cathode-ray tubes (CRTs). Liquid crystal displays (LCDs) have now become common for desktop as well as laptop computers. LCDs also are used in some television sets, and in projection televisions, which project an image onto a large screen. Plasma panels are less common, but used for some large-screen televisions. All these displays show standard video and computer formats.

Digital Television

Digital cable and DVDs are compatible with old televisions; HDTV is not.

Video signals can be digitized like any other analog signal. With the advance of digital technology, video signals increasingly are being transmitted in digital form. However, there are two different types of digital transmission developed for different types of television sets. One is essentially a digital version of standard television; the other delivers a higher-resolution image.

Satellite systems, cable systems, and DVDs (Digital Versatile Disks) all provide digital signals that are compatible with conventional NTSC television. Electronic interfaces built into a DVD player or provided in satellite or cable tuners convert the digital signal into NTSC analog format. You can plug a satellite dish or a DVD player into any standard NTSC set that has a suitable video or antenna input. The pictures are sharper and clearer than normal broadcast television or video cassettes, but the difference isn't dramatic. You still get a nominal 525 lines per screen.

The new digital standard for HDTV is different. This standard is intended for new large-screen televisions that can display up to twice as many lines per screen as NTSC television, but also can be used for smaller sets. These new digital televisions can't display NTSC television, and NTSC sets can't display signals in the new digital format without a special adapter. HDTV will require many changes in cable television and broadcasting, so we'll consider it in more detail.

High-Definition Television (HDTV)

North America, Europe, and Japan have separate HDTV standards.

The consumer electronics industry began campaigning for a new generation of high-definition television technology in the 1980s. Their goal was to offer larger, wider images of better quality and—not coincidentally—to make money by selling a new and more expensive generation of large-screen television sets. Japanese electronics firms developed analog HDTV, but after lagging on analog systems, American industry switched to digital transmission and developed a digital HDTV standard that was accepted by the Federal Communications Commission. Europe and Japan are implementing their own digital HDTV standards.

Officially, the U.S. standard is known as the *Digital Television (DTV)* standard of the Advanced Television Systems Committee. It includes 18 distinct digital video formats with different numbers of scan lines and screens per second. Six are classed as high definition and the other 12 are standard definition television (SDTV), which offers somewhat better image quality than NTSC analog television. The HDTV formats are intended for large-screen sets; the SDTV formats are for smaller screens. Table 27.2 lists these formats.

Digital television supports several levels of screen resolution.

A single digital signal will support all these formats. Digital electronics in new sets will decode the signal to produce a display that matches the screen. This compromise allows both the interlaced scanning preferred by the television industry and the progressive scanning preferred for computer displays. The different picture sizes accommodate the variety of television set sizes.

Broadcast HDTV is compressed to 19.3 Mbit/s

Broadcast HDTV digitally compresses signals by a factor of 75, reducing the data rate to 19.3 Mbit/s. Digital compression does degrade signal quality, so video production and archival storage use the lower degrees of compression listed in Table 27.3. Video producers avoid compression techniques that depend on the sequence of frames, which could

Table 27.2 Advanced television digital formats

Picture Size (Lines High by Pixels Long)	Frames per Second	Aspect Ratio
1080 × 1920	60 interlaced	16:9 (wide-screen)
(HDTV)	30 progressive	
	24 progressive	
720 × 1280	60 progressive	16:9 (wide-screen)
(HDTV)	30 progressive	
	24 progressive	
480 × 704	60 interlaced	16:9 (wide-screen)
(SDTV)	60 progressive	
	30 progressive	
	24 progressive	
480 × 640	60 interlaced	4:3 (conventional)
(SDTV)	60 progressive	
	30 progressive	
	24 progressive	

change during editing. (The digital signals on DVDs and digital cable channels also are compressed, but not by as large a factor; digital cable delivers 5–5.5 Mbit/s.)

The high compression of HDTV used in the U.S. system allows the signal to be transmitted in a radio band only 6 MHz wide, the same width as NTSC channels. This retains the channel structure used for analog broadcasting and for transmitting video signals in cable-television networks, although channel assignments change.

All the interested industries lobbied Congress and the FCC heavily to assure that they got some benefits from the change from analog to digital. Broadcasters persuaded Congress to give every television station a free digital channel, as long as they meet deadlines for turning on digital transmitters and agree to return their analog channel to the FCC. The cellular telephone industry will claim the high-frequency end of the old broadcast television

Table 27.3 Compression levels for HDTV

Task	Compression Ratio
Video production	4:1
Archival storage	25:1
Transmission	75:1

THINGS TO THINK ABOUT

The HDTV Mess

Many problems have slowed the switch from NTSC analog television to HDTV digital television, and more are likely to emerge.

- Broadcasters, electronics manufacturers, and the entertainment industry delayed in making needed changes until Congress and the FCC agreed to provisions they wanted, so digital video products came to market very slowly.
- The public was reluctant to start buying HDTV-compatible televisions because the real benefits of HDTV come with large screens, and large-screen sets are very expensive.
- HDTV broadcasts also slipped behind schedule, giving those who bought HDTV receivers little to watch.
- Cable television systems were slow to offer programs in HDTV format because they had only a limited number of channels available.
- Flaws in the U.S. HDTV broadcast standard may make digital signals harder to receive than analog signals.

Clearly 85% of television viewers won't have HDTV-compatible televisions by the end of 2006. Should some group give digital-to-analog converters to the people who still have analog sets? If so, should that group be the industries that benefit from the switch to digital television or the government? Or will the people with analog sets have to foot the bill if they want to continue receiving television signals?

The communications industry affects us all, and we should think about how this change will be implemented, who will pay for it, who will benefit from it, and what the side effects will be. If nothing else, someone will have to deal with all the obsolete television sets, which some states regulate as toxic waste because the picture tubes contain lead.

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spectrum once analog transmission stops. Entertainment producers were reluctant to adopt HDTV unless restrictions were imposed on copying of programs in digital form.

Analog TV broadcasts are supposed to stop in 2006.

Stations are scheduled to stop analog broadcasts in 2006—provided that at least 85% of viewers in their area have sets that can receive digital broadcasts. That isn't going to happen, but the cell phone industry is still lobbying intensely to shut down analog television broadcasts in the bands they want. The timetable for the transition from analog to digital is unclear, but the political pressures and lobbying are sure to get intense.

Transmission Media

So far I haven't said much about how video signals are distributed. Because this is a book on fiber optics, our main interest is in the use of fiber in cable television systems. However, you also should know a bit about other important transmission technology: ground-level broadcast at radio or microwave frequencies, satellite broadcast at microwave frequencies, and coaxial cables.

Terrestrial Broadcast

Television began as a broadcast medium, with local stations transmitting radio-frequency signals from tall antennas. NTSC, PAL, and SECAM standards were all based on the assumption that signals would be broadcast from terrestrial towers to antennas connected to home receivers. The radio waves induce small electrical currents in the antennas and receivers amplify and process the signal to extract the video. Government agencies assign specific frequencies for stations to use at their locations. Other stations may use the same frequencies if they are far enough away that the signals will not interfere.

Local stations broadcast at radio frequencies on assigned channels.

The U.S. HDTV signal was also designed for broadcast, in the same 6-MHz frequency bandwidth assigned to an analog broadcast. The Federal Communications Commission assigned each station a second channel for digital broadcasts, at a different frequency than any analog channel used in the area, but in the same band of channels assigned to television broadcast. Digital signals are not supposed to interfere with analog broadcasts.

Microwave Rebroadcast Services

Your television antenna can only receive broadcast signals from stations near you. Some services use microwave frequencies to distribute signals from distant stations and premium services, such as Home Box Office, to paying subscribers. These services include direct broadcast satellites and local multipoint distribution services.

A *direct broadcast satellite* transmits many video signals simultaneously in the microwave band to subscribers with small dish antennas and decoders. The transmitting satellite is placed in an orbit above the equator so it circles the planet exactly once every 24 hours. This makes it appear to stay in place above the same point. Its transmitting antenna beams microwaves to the area it serves. This design allows a single transmitter to cover most of the United States, including rural areas where cable service is usually unavailable.

Satellites broadcast microwave signals that carry many channels.

A *local multipoint distribution service* (LMDS) is a fixed wireless system that transmits microwave signals from many small terrestrial antennas distributed in its service area. Each antenna broadcasts signals over a small area, like a cell phone, but it distributes signals to fixed receivers. This distribution of antennas allows the system to offer two-way services such as high-speed data, teleconferencing, interactive video, and voice telephone service. The service also can distribute video signals to subscribers in the same way as direct broadcast satellites.

So far, direct broadcast satellites are much better developed and are posing a serious challenge to cable television. Few fixed terrestrial systems have been installed. Direct broadcast satellites usually transmit digital video, encoded for microwave transmission.

Cable Television

Cable television began as community antenna television (*CATV*, an acronym still used by the industry), which delivered broadcast television signals to people who otherwise could not receive them. The system operator built one big antenna to pick up broadcasts from distant stations, then distributed the signals through cables to local subscribers. Eventually the concept spread to urban and suburban residents who could receive broadcast signals, but wanted better reception or more channels. More features have been added since.

Cable television's core business is video.

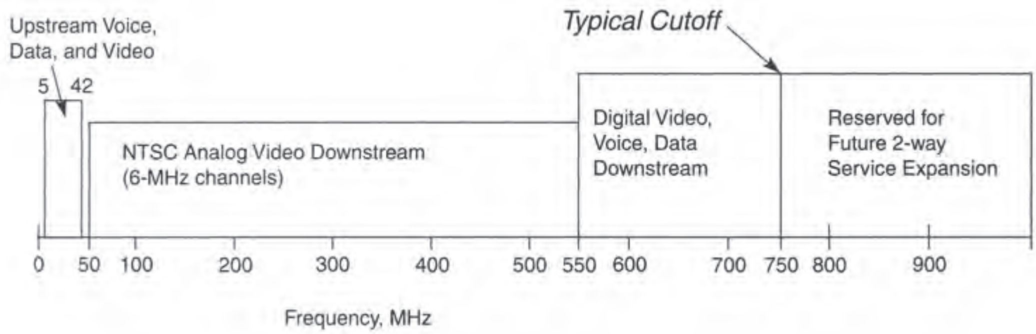

FIGURE 27.4
Spectrum of hybrid fiber/coax.

The core business of a cable system is distributing video channels to subscribers. Basic service usually includes local channels and selected national channels, and is transmitted to all subscribers in unencrypted form. Premium video channels are encrypted, so they can be viewed only by subscribers who pay for special decoder boxes. Modern cable systems offer both analog and digital channels, with basic services in analog form and some premium channels in digital format. In general, the digital signals today are *not* HDTV format; the digital format offers higher quality than analog transmission, but like DVDs it does not offer dramatically higher resolution than standard analog television. Many cable systems with digital service also offer video on demand, which allows customers to select particular programs to be transmitted directly to their homes through the cable system.

Video, voice, and data are bundled as "triple-play" services.

Modern cable networks also provide voice and data services over special channels set aside for those purposes. They were the first to offer customers bundles of "triple-play" services that standard telephone lines do not have the bandwidth to offer. To add video service, phone companies must either install fiber to homes, build terrestrial microwave networks for video distribution, or form partnerships with satellite television companies.

Cable systems can transmit frequencies as high as 650 MHz to 1 GHz through their network of fiber-optic and coaxial cables. The upper limit of a particular system depends on its design and the equipment it uses, but coax attenuation becomes a problem above 1 GHz. That spectrum is divided into three basic blocks, as shown in Figure 27.4. Frequencies of 5 to 42 MHz typically are reserved for upstream voice, data, and video. Frequencies from about 50 to 550 MHz are reserved for upstream video signals transmitted in standard NTSC analog format, each with its own 6-MHz band. Higher frequencies generally are reserved for digital television channels and downstream voice and Internet connections, with the number of channels available depending on the system. However, these digital signals are converted into analog format for cable transmission.

Cable companies will phase in HDTV by replacing old NTSC video channels, since HDTV signals fit in the same channel bandwidth.

Cable Television Architecture

Hybrid fiber/coax combines fiber and coax.

The dominant technology for cable television today is called *hybrid fiber/coax (HFC)*. Fiber-optic cables distribute signals from a control center called a *head-end* to neighborhood distribution nodes. Coaxial cables distribute signals from neighborhood nodes to individual

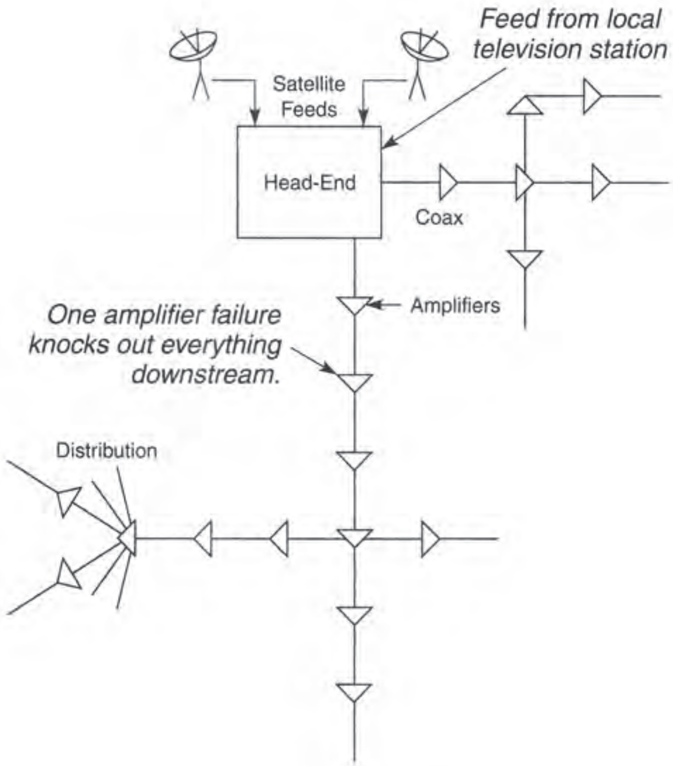

FIGURE 27.5
All-coax cable network required many in-line amplifiers.

homes. This structure has evolved over the years to take advantage of fiber to meet the growing demand for video service.

Basic Cable System Structure

Early cable networks were one-way tree systems with cables radiating from the head-end, as shown in Figure 27.5. The head-end received video signals from satellite dishes and local television stations, and multiplexed them into 6-MHz slots in an analog radio-frequency signal that it distributed through coaxial cable. The high attenuation of the coax required that amplifiers be installed about every 600 meters (2000 feet) along the cable. This delivered the signal, but long chains of analog amplifiers introduce noise and distortion into the signal. Even worse, an amplifier could fail, which would knock out service to everyone downstream.

Coax requires amplifiers about every 600 m.

Fiber has much lower attenuation than coax, so it replaced coax in the *trunk lines* going from the head-end to the local distribution nodes. This eliminated the need for amplifiers in trunk lines, improving the quality of the signal reaching subscribers and greatly reducing the chance of failure in the distribution network.

Cable networks transmit analog signals, so they must convert digital signals to an analog form at the head-end, just as modems convert digital data into analog form for transmission over phone lines. This requires the use of highly linear laser transmitters located at the head end to send signals through single-mode fiber trunk cables. Meeting the cable industry's performance requirement was a challenge, and required the development of highly linear distributed-feedback laser transmitters, which now are standard in cable systems.

Cable systems use linear analog laser transmitters.

Hybrid Fiber/Coax Network Structure

Fiber trunks link head-ends to distribution nodes.

Fiber trunk cables deliver the analog signals to local distribution nodes, which convert the optical signals into electronic form and distribute them through coaxial cable to homes in the neighborhood. Traditionally, typical nodes in hybrid fiber/coax systems serve 500 to 2000 homes, but the trend is toward nodes serving fewer homes. Thick coaxial cables connect the head end to the nodes, but the drop cables are a thinner and lighter grade of coax. These distribution cables require few amplifiers.

Figure 27.6 shows a representative hybrid fiber/coax distribution network. The head-end collects video signals from local television stations and satellite feeds. It also links to the telephone network and the Internet for voice and data service. Fiber trunks run from the head-end to distribution nodes; they also may run to secondary hubs, which connect to their own sets of distribution nodes. The distribution nodes convert the optical signals into electronic form and transmit them to subscriber homes through coax. Likewise, they convert electronic signals from subscribers into optical format and send them through the fiber to the head-end. The illustration shows that cable amplifiers may be needed to span the full distance from the distribution node to subscribers.

Hybrid fiber/coax is a tree-and-branch network.

Like the original cable television network, hybrid fiber/coax is fundamentally a tree-and-branch structure, which physically distributes the same signals to groups of subscribers. The electronic decoder (set-top box), which the cable company supplies, determines which video channels the subscriber can receive depending on what services they pay for.

Voice and data services are distributed like data through a local-area network; each signal physically goes to all the terminals, but only the one addressed by the signal pays any attention. How voice and data signals are distributed from the cable node depend on the customer base. If the node serves 500 homes and most of them have cable modems, the node may have separate branches going out to 25 groups of 20 homes each. All the homes on each branch effectively share a local-area network for cable modem service.

Hybrid Fiber/Coax Transmission

Cable bandwidth can reach 1 GHz, but most cable systems transmit only to 750 MHz.

The combination of fiber-optic trunks and coaxial distribution is widely accepted as hybrid fiber/coax. It allocates frequencies in the analog cable spectrum as shown in Figure 27.4. The 5- to 40-MHz band is allocated for upstream data, voice, and video signals from subscribers. Standard NTSC video is transmitted at 50 to 550 MHz. These bands overlap standard television broadcast bands, but only a few broadcast channels transmit at the same frequency on cable systems. Frequencies higher than 550 MHz are allocated for premium channels transmitted in digital form, and for the downstream portion of telephone and data traffic. Typical cable systems reserve 550 to 750 MHz for digital video as well as additional capacity for future expansion of video and two-way services. One consequence of this design is that cable modems have more bandwidth to transmit downstream to subscribers than subscribers have to transmit upstream. Total bandwidth of the cable network potentially can reach 1 GHz.

Upstream and downstream signals travel simultaneously in opposite directions in the coax part of a hybrid/fiber coax network. The fiber part of the network separates signals by transmitting them either through different fibers or at different wavelengths through the