# CHAPTER 17.3

# LOCAL ACCESS NETWORKS

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## INTRODUCTION

The invention of the telephone in 1876 began an era of communications by voice over great distances. In order for telephone communications to be effected there needed to be low cost connections between telephones that could transmit voice signals with minimum attenuation and interference. Copper wires had the best balance of cost, tensile strength, durability, and transmission performance for the purpose. For economy it was thought that one wire between each pair of telephones with ground return would be adequate. This was not the case because of high direct and induced interference in the wires so connected. The use of a balanced pair of wires improved performance although it increased the cost of a connection by over 50 percent.

It was not practical to connect every pair of telephones with dedicated wires. Central switching offices were created where dedicated lines from telephones in the vicinity of the office could be terminated and flexibly connected to lines associated with other telephones as required to place a call. By the 1890s initial installations of automatic switching equipment began in local central offices to make connections between local *loops*, the name given to the pair of wires between the telephone and the central office and between loops and *trunks*, the name given to wire pairs between central offices. Over the years intercentral office or, simply, interoffice trunks of many varieties have been developed to support toll, tandem, equal access toll, and other applications.

The first telephone loops and trunks were pairs of uninsulated wires strung along aerial pole lines between terminations. As the number of telephone lines grew in the 1880s, these *open wires* proved to be impractical in urban applications. Cables of pairs of insulated wires were invented in the 1880s to improve the physical efficiency of aerial telephone lines and to make possible the placement of underground lines. After much trial and error, paired cables, consisting of wires insulated by paper wrappings, were perfected and standardized by 1888.

By the early 1900s the modern wireline telephone networks had taken shape and have not changed much since (Fig. 17.3.1). The term local access in the context of a wireline network means the local loop facilities between the central office and the end user's premises. Until 1976, telephones and other end-user line-terminating equipment were part of the local access network and were provided by the locally franchised telephone company. In 1976 the FCC separated line terminating equipment such as telephones, private branch exchanges, data modems, and the like into an unregulated category of equipment, called customer premises equipment or CPE under Part 68 rules. Although the various types of CPE play an integral role in the transmission and signaling performance of telephone networks, they are not considered part of the local access network. Part 68 incorporates rules governing the protection of the network and so-called third parties (parties not participating in a telephone connection) from nonconforming CPE or combinations of CPE. Part 68 contains no network or end-to-end compatibility information.

The Exchange Carrier Standards Association (ECSA) codifies network interface standards between CPE and local access networks in the form of American National Standards Institute standards adopted from standards developed under the ECSA T1 Committee. Customer premises equipment standards are established by the Telecommunications Industry Association (TIA) and are generally based on pre-1976 telephone set and other CPE properties.

## *TELEPHONE LOCAL ACCESS-LOOP DESIGN AND TECHNOLOGIES*

### Design Based on Wire Pairs

Design of wireline local access facilities or loops must economically accommodate two fundamental characteristics of the society being served: (1) the tendency for the population of end users to be clustered around population centers with decreasing density as a function of increasing distance from the center and (2) the presumption that service will be provided within a day or so of a request. The first characteristic suggests the location of a central office near the center of population with decreasing numbers of lines in the local loop plant as distance from the central office increases. The second characteristic suggests a continuous inventory of unused lines available everywhere in the community to meet unscheduled demands for service.

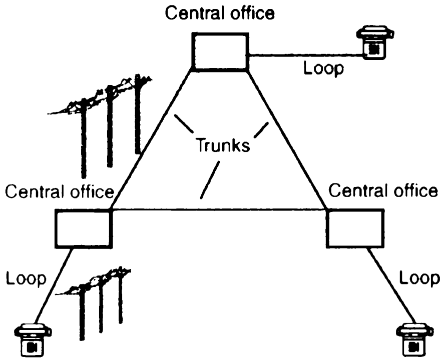


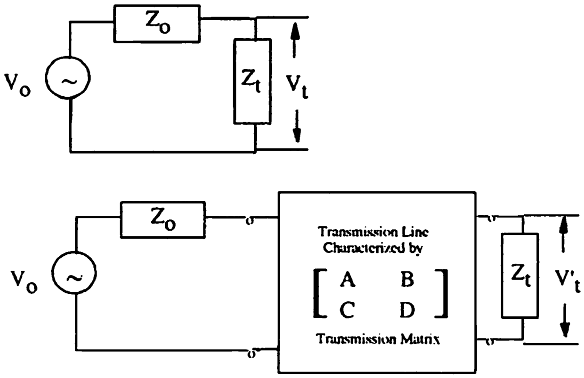
**FIGURE 17.3.1** Local telephone network, basic layout.

The characteristics of human hearing and voice have a further influence on the design of the local loop plant. Copper wire pairs have dc resistance and attenuate alternating current signals. The frequency range of human hearing is generally considered to be from 100 Hz to about 20,000 Hz and is sensitive to sounds over many orders of magnitude of sound pressure intensity. The human voice contains 80 percent of its energy at frequencies below 1000 Hz and over 80 percent of articulation in frequencies below about 3000 to 4000 Hz. Faithful transmission of the human voice using energy in the frequency range between 300 and 3000 Hz provides efficient, intelligible, and recognizable communication over telephone networks.

Copper wires of larger diameter provide lower attenuation per unit length but are more expensive. In the early days of telephony, before the advent of electronic signal amplification, load coils were used to alter the transmission properties of wire pairs to reduce the attenuation of signals in the voice frequency band. The most common arrangement in the local loop is to place 88 mH coils in series with wire pairs every 6000 ft beginning 3000 ft from the central office. This technique, referred to as H88 loading, allows finer gauge wires to be used for economy at distances greater than about 18,000 ft from central offices, about 25 percent of local loops.

Similarly, there was no need to design telephone transmitters and receivers to operate effectively outside of the range of about 300 Hz to 3000 Hz. The technology employed in telephone sets for the first 100 years for the conversion of acoustic speech to electrical signals and vice versa remained essentially unchanged. The carbon microphone transmitters and electromagnetic diaphragm receivers used had limited efficiency and dictated, along with average acuity and comfortable speaking volume, the maximum voice frequency signal attenuation that could be tolerated on a connection experiencing acceptable background noise. The last major improvement in telephone set efficiency occurred in 1951 with the introduction by AT&T of the model 500 set, which properties are the basis for the current TIA standards for telephone set performance. Although new technologies exist that might further improve telephone set efficiency, 500 set equivalence is all that is required to match the characteristics of network connections and human speech and hearing comfort levels.

The design of local loops was influenced by voice frequency transmission across telephone connections as well as by early telephone properties. A typical telephone connection in a metropolitan area might involve two loops and one trunk connection. To minimize the total cost of network construction it was necessary to balance the performance of such connections against the cost of the networks needed to create the connections. Larger wire gauges improved transmission performance but increased cost. More central offices closer to customers reduced loop lengths and costs but increased the number of trunk routes required between more numerous central offices. Early designs balancing these factors resulted in loops with an average length under 2 mi and paired cables with wire gauges of 19, 22, and 24 AWG. Wire of 26 AWG was introduced in the 1920s. To achieve satisfactory voice transmission local loop designs were adopted over time that limited the maximum insertion loss at 1000 Hz to less than 8 dB with terminations simulating a telephone set at one end of the loop and a switching system line termination at the other end. Insertion loss is



$$\text{Insertion Loss} = 20 \log (V_t/V'_t)$$
$$= 20 \log (|(AZ_t + B + (CZ_t + D)Z_o)/(Z_o + Z_t)|)$$

**FIGURE 17.3.2** Definition of insertion loss of a transmission line.

defined in Fig. 17.3.2, which refers to A, B, C, D parameters to characterize transmission lines. These parameters are defined by the characteristic impedance and propagation constant of a transmission line and are discussed later in this section.

Loop design was also influenced by the operating characteristics of electromagnetic relays employed in central office switching system line circuits. The signaling protocol between telephone sets and switches is based on the flow or not of direct current from batteries in the central office through the off-hook telephone set or other CPE. Batteries with a nominal voltage of 48 V dc had a minimum value of 45 V dc in the 1950s. The relays commonly used in the early 1950s operated reliably on currents as low as 23 mA. This dictated a loop design that presented a maximum dc resistance, including the resistance of the line circuit and the telephone set to 45/.023 = 1956 Ω. In the 1950s maximum telephone set resistance was less than 220 Ω and line relay winding resistance was less than 440 Ω with high probability, leaving about 1300 Ω for the wire pair between the central office and the customer's premises. In 1954 AT&T adopted loop design rules referred to as Resistance Design rules using 1300 Ω as the maximum loop resistance, assuming the use of 500-type telephone sets or equivalent.

Resistance Design rules used a combination of H88 loading, maximum loop resistance, and 500-type telephone set properties to achieve the goal of bounding the performance of the loop at satisfactory loss level while achieving economy in loop design. The Resistance Design rules are summarized as follows:

1. Maximum loop resistance less than 1300 Ω at operating temperatures.
2. Maximum nonloaded loop length 18,000 ft with bridged tap < 6000 ft.
3. All loops greater than 18,000 ft use H88 loading rules.

Bridged tap is a pair of wires that branches off another pair at a junction point. At voice frequencies bridged tap acts as a capacitive load and increases attenuation.

Resistance Design rules promote voice frequency transmission performance that is consistent with residential telephone service quality requirements (less than about 8 dB insertion loss at 1000 Hz). These rules also ensure satisfactory operation of central office switch dc and voice frequency signaling circuits to the low voltage discharge level of central office battery supplies in the event of an extended power outage and the failure of emergency generators to operate.

Figure 17.3.3 illustrates application of Resistance Design principles applied to a cable route of 18,000 ft. A line is drawn parallel to the 24-gauge line so that it intersects the 1300-Ω ordinate at the 18,000 ft abscissa value. The intercept with the 26-gauge line shows that a combination of 11,700 ft of 26-gauge cable and 6300 ft of 24-gauge cable will result in an 18,000-ft cable route that just meets 1300-Ω loop resistance.

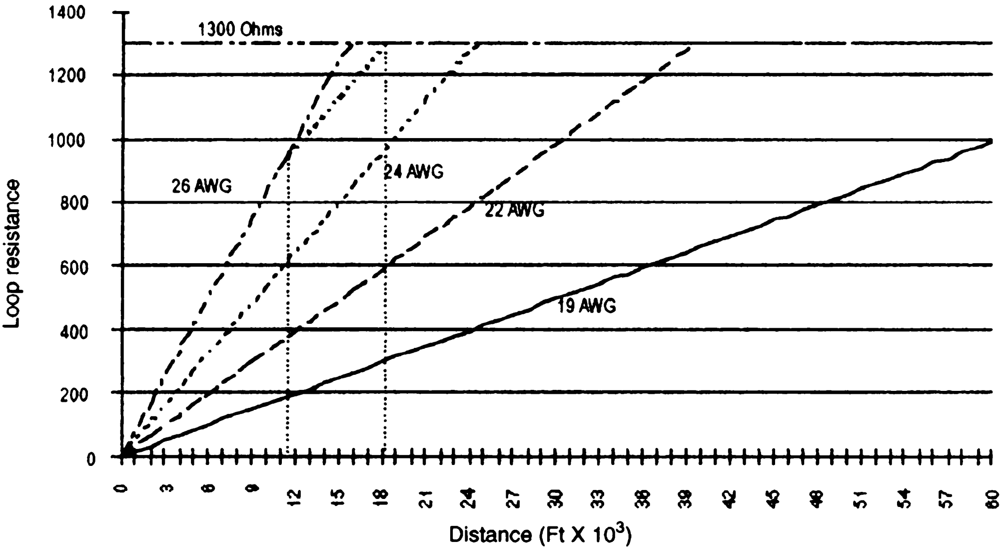


FIGURE 17.3.3 Example resistance design application.

The Resistance Design limit was increased to 1500 Ω in the early 1980s based on the improved dc current sensitivity of electronic switching system line circuits and the finding that the 500-type telephone set transmitter was more efficient at a loop current of 20 mA by about 2 dB than had previously been thought. Figure 17.3.4 shows the statistics of telephone loop length over the period from 1963 to 1983. It can be seen that average loop length increased slightly over the period. This resulted from the growth of suburbia with reduced housing density and the consolidation of smaller central offices into fewer, larger central offices.

## Structure Based on Cables of Wire Pairs

In planning new paired cables for telephone local loops, engineers anticipate potential future demand. An economical design will provide just enough copper pairs at the right locations to satisfy demand for some time into the future so that the goal of near instant satisfaction of requests for service can be met. The new cables must be added before existing cables are full. Yet, the design must not place excessive capacity that will never be required and thereby become stranded investment. Elaborate computer aids have been developed over the years, principally by AT&T, using economic theory based on the time value of money with constraints of technology choices, tax policies, and regulatory rules to assist engineers in developing plans for building or adding to local loop cable plant. Discussion of the use of these aids and the underlying economic theory is beyond the scope of this section. However, there are two considerations that limit the choices of solutions using paired cables: the performance of twisted pair copper cable technology and the administrative structure of the areas to be served.

## Copper Cable Technology

Cables consisting of copper wire pairs began to be manufactured at the end of the 1880s. The wires in each pair were twisted around one another to reduce the electromagnetic coupling, called crosstalk, with nearby pairs. Bundles of 50 or 25 pairs, called units or binder groups, are assembled into cables of up to 2700 pairs. The number of pairs possible to be bundled into a single cable is constrained by the maximum allowed cable diameter (less than 3 in. due to the diameter of underground ducts through which cables may be pulled), wire

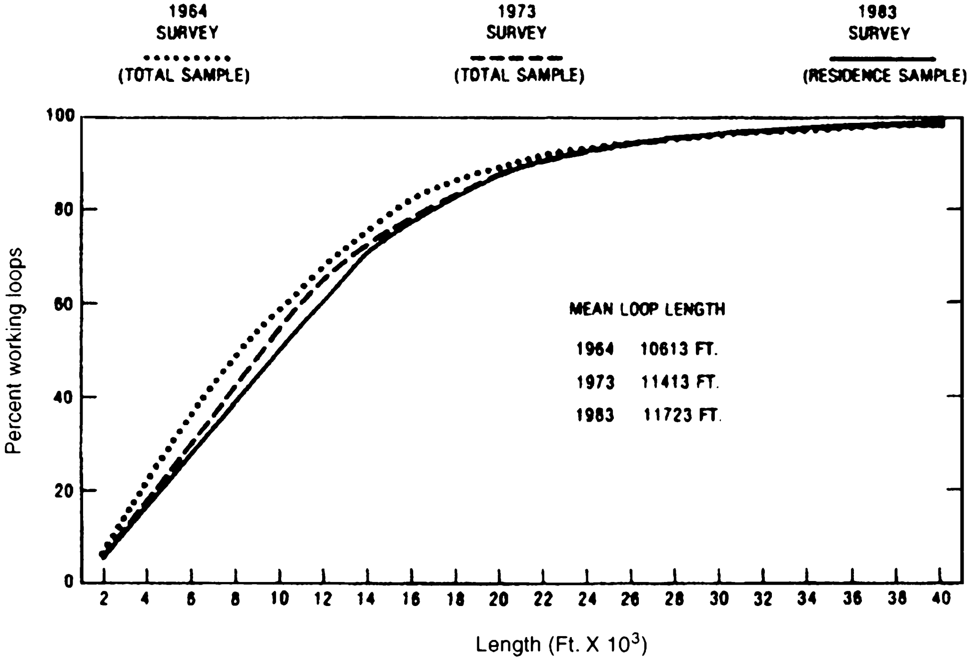


**FIGURE 17.3.4** Loop length statistics resulting from economic design principles.

gauge, wire insulation thickness, and sheath thickness. The wires are insulated from each other using a variety or materials. Paper insulation proved to be most practical in the early days of telephony. Paper produced lower attenuation than materials with a higher dielectric constant as long as the paper was kept dry. Wires were later coated with wood pulp, called pulp insulation, to allow the design of compact cable structures. Paper insulation was used in a majority of cables into the 1930s. Plastic insulation materials such as polyethylene became predominant in the 1960s. The density of pairs in polyethylene insulated cables was improved in the 1970s by introducing air bubbles into the plastic, reducing its effective dielectric constant so that the insulation coating on the wires could be of reduced diameter while maintaining the standard capacitance between the wires in the pair. This form of insulation is called "expanded" insulation.

The bundle of twisted pairs form the core of the cable, which is surrounded by a sheath. Early sheaths consisted mainly of an extruded lead jacket that kept water out of the core, provided some shielding against external electromagnetic interference and diverted lightning discharges to earth. Modern cable sheaths typically have an extruded outer polyethylene or polyvinyl chloride jacket covering a metal shield made of corrugated aluminum or steel wrapped around an inner jacket of polyethylene extruded over the core of the cable. Some typical lead sheath cable cross-sections of the past are shown in Fig. 17.3.5.

Early cable designs in the 1880s suffered from lack of standards and from increased attenuation compared to open wire pairs. By the late 1880s, standards were established that ensured predictable performance in dry cables. The two principal attributes for paired cable standardization have been wire diameter (gauge), which dictates the resistance of the wire, and capacitance per unit length. Resistance and capacitance largely control the voice frequency transmission performance of the pairs and resistance controls the dc signaling range of operation. The attenuation limitations of twisted pairs were first addressed by improvements in telephone set transmitter and receiver efficiencies. This was augmented by the use of inductive loading which trades lower voice frequency attenuation for greatly increased attenuation at frequencies above the voice range. Finally, electronic circuits came to be used to compensate for wire pair attenuation. In the local loop the use of electronics became commonplace in the 1970s.

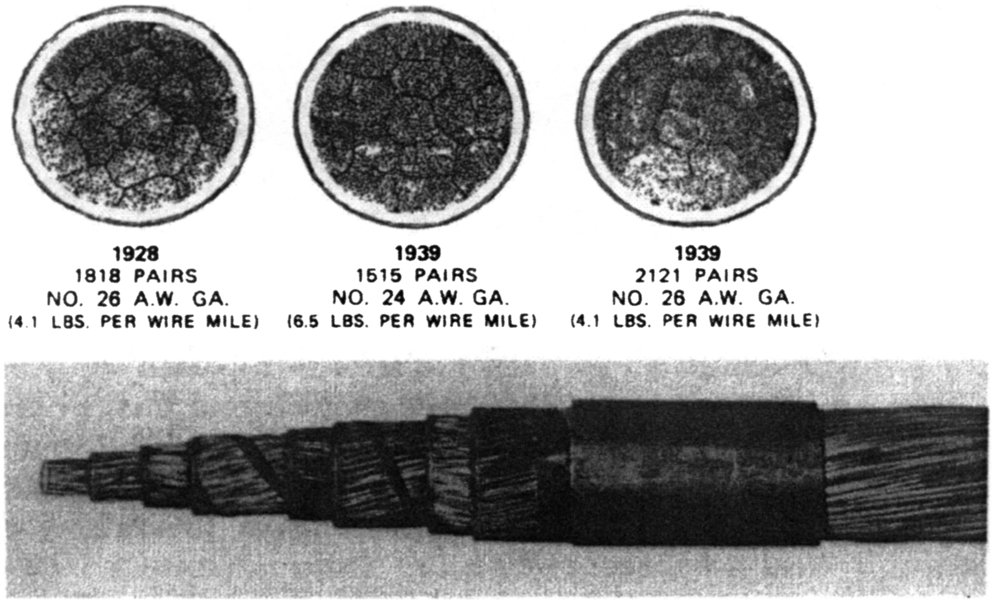


**FIGURE 17.3.5** Representative larger size twisted pair cables.

Table 17.3.1 gives example measured values of the resistance, capacitance, and variability of those quantities per 1000-ft length of typical paired copper cables.

The nominal value of capacitance used in most engineering studies is 15.7 nF/1000 ft or 83 nF/mi for local loop applications. The nominal value of inductance of twisted pairs is about 1 mH/mi or 189 $\mu$H/1000 ft.

Twisted pairs in a local access application experience three fundamental transmission impairments: propagational attenuation and distortion, crosstalk, and induced noise (other than crosstalk). Induced noise from external sources of interference is mitigated by the cable shield and its ground connections. Crosstalk is reduced by staggered twist lengths from pair to pair and matched impedances between each wire in a pair and the cable shield (balance). Signal propagation is a function of the primary constants of a cable (resistance *R*,

**TABLE 17.3.1** Electrical Characteristics of Paired Copper Cables

| Gauge | Insulation | No. Pairs | R (Ω/1000 ft) | Std. Dev. (R) | C (nF/1000 ft) | Std. Dev. (C) |
|---|---|---|---|---|---|---|
| 26 AWG | pulp | 300 | 83.6 | 0.65 | 15.38 | 1.57 |
| 26 AWG | PIC | 100 | 86.0 | 0.69 | 15.12 | 1.23 |
| 24 AWG | PIC | 600 | 53.4 | 0.56 | 15.38 | 0.66 |
| 24 AWG | DEPIC | 50 | 51.9 | 0.36 | 15.54 | 0.61 |
| 22 AWG | PIC-wp | 100 | 33.9 | 0.14 | 15.31 | 0.79 |
| 22 AWG | PIC | 50 | 34.7 | 0.14 | 15.52 | 0.68 |
| 19 AWG | PIC-wp | 50 | 16.7 | 0.14 | 15.63 | 0.70 |
| 19 AWG | DEPIC-wp | 25 | 16.3 | 0.15 | 15.79 | 0.62 |

PIC = polyethylene insulated conductor
DEPIC = dual, expanded polyethylene insulated conductor
wp = waterproof (filled cable)

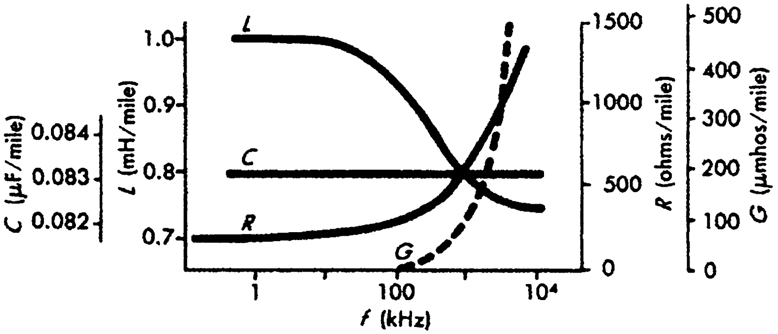


**FIGURE 17.3.6** Representative primary constants for 22-gauge PIC copper pair.

capacitance *C*, inductance *L*, and conductance *G*, per unit length). Propagation of signals is characterized by the characteristic impedance $Z_c$ and propagation constant Γ with the following relationship to the primary constants:

$$\Gamma = \sqrt{(G + i\omega C)(R + i\omega L)} \qquad \text{and} \qquad Z_c = \sqrt{\frac{(R + iwL)}{(G + iwC)}}$$

*R*, *L*, and *G* and functions of frequency. At frequencies below 0.1 MHz, G is negligible. *R* and *L* are approximately constant in the voice frequency range. At higher frequencies *R* increases as the square root of frequency and *L* decreases as the square root of frequency. Figure 17.3.6 illustrates the behavior of these parameters with increasing frequency for a typical 22 AWG copper twisted pair over a wide range of frequencies. Figure 17.3.7

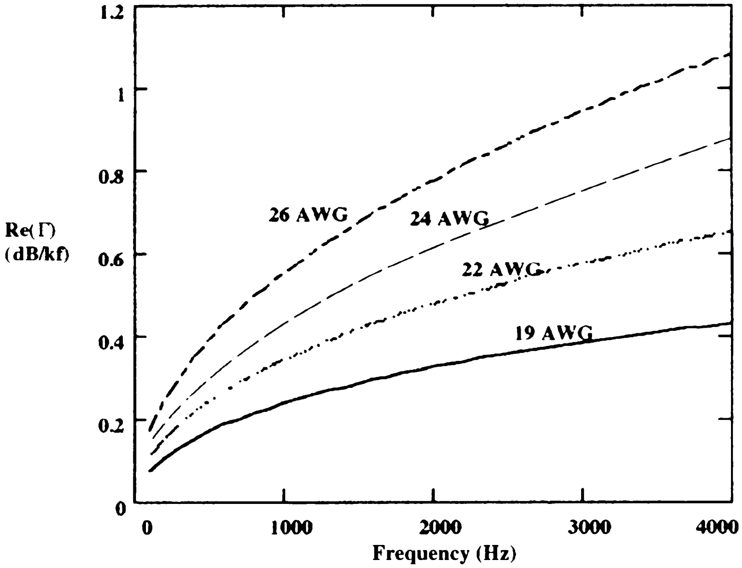


**FIGURE 17.3.7** Attenuation of 19, 22, 24, and 26 AWG PIC copper pairs.

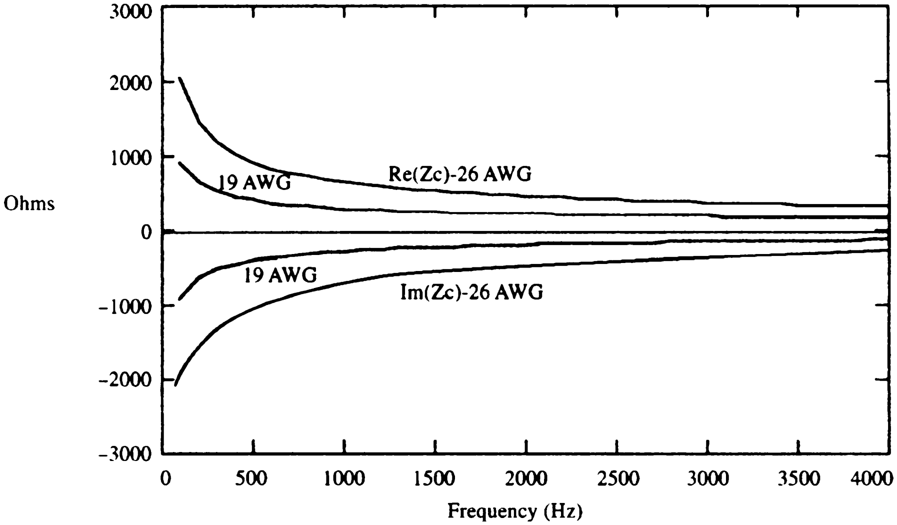


**FIGURE 17.3.8** Characteristic impedance of 19 and 26 AWG pairs at voice frequencies.

shows the attenuation (real part of Γ) of 19-, 22-, 24-, and 26-gauge pairs in the voice frequency range. $Z_c$, the characteristic impedance of a twisted pair, is illustrated for 19- and 26-gauge pairs in Fig. 17.3.8. At frequencies above the voice band $Z_c$ approaches a resistive value of about 100 ohms.

The effect of H88 loading is illustrated in Fig. 17.3.9 for the case of an 18,000 ft long, 26 AWG loop. The figure shows the insertion loss (see Fig. 17.3.2 for a definition) of a loop with and without load coils at 3000 ft,

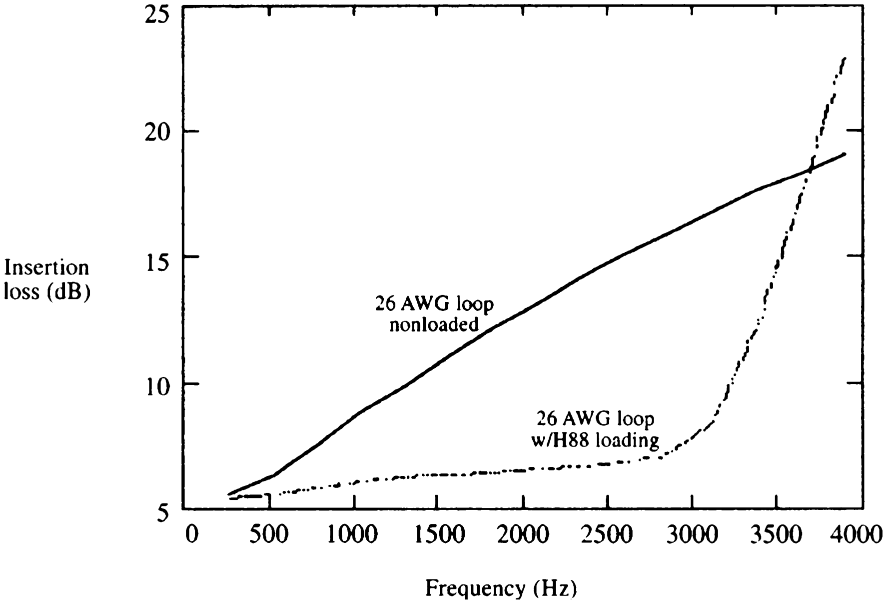


**FIGURE 17.3.9** Insertion loss of 18,000 ft of 26 AWG loop, nonloaded and with H-88 loading.

9000 ft, and 15,000 ft from the central office. Terminations at each end of the loop were assumed to be 900-Ω resistors. The transmission matrix for a transmission line of length, 1, is given by

$$A = D = \cosh \Gamma 1, \quad B = Z_c \sinh \Gamma 1, \quad \text{and} \quad C = \sinh \Gamma 1/Z_c$$

The transmission matrix for a load coil is given by

$$A = D = 1,\ C = 0, \quad \text{and} \quad B = 5.4 + i\omega.088$$

As shown in Fig. 17.3.9, the load coils cause the insertion loss to be lower and less variable to about 3000 Hz and to increase much more rapidly with frequency above 3000 Hz. In practice the terminations will not be resistive. During the course of a telephone call the impedance at the central office will be that designed into the line circuit of the switching system, typically a 900-Ω resistor in series with a 2.16 $\mu$F capacitor. At the user end of the loop the impedance will be that of an off-hook telephone, a quantity that is only loosely characterized and that typically varies with the dc current supplied by the switching system or other line circuit through the loop. Figure 17.3.10 illustrates a model for the impedance of an off-hook 500-type telephone set at two representative values of dc loop current. A resistive value of 600 Ω is often used as an approximation.

Crosstalk is the coupling of electromagnetic energy from one pair to another. The two most important forms of crosstalk are near end crosstalk (NEXT) and far end crosstalk (FEXT). NEXT is the coupled signal sensed at the same end of a circuit as the source of the unwanted signal. FEXT is the coupled signal sensed at the end of the circuit distant from the source. These types of crosstalk are illustrated in Fig. 17.3.11. NEXT is most important as an impairment in circuits that transmit signals in the same frequency range in both directions, e.g., T1 carrier lines. FEXT is more important where signals in the two directions through adjacent pairs use separate frequency bands, e.g., analog carrier systems. NEXT increases approximately as the 3/2 power of frequency and relatively insensitive to loop length. FEXT increases approximately as the square of frequency and increases with the length of the loop.

The attenuation of crosstalk interference into a pair from another pair in a cable is called crosstalk loss. Crosstalk loss exhibits a random distribution between any pair in an $n$-pair cable and the other $n - 1$ pairs.

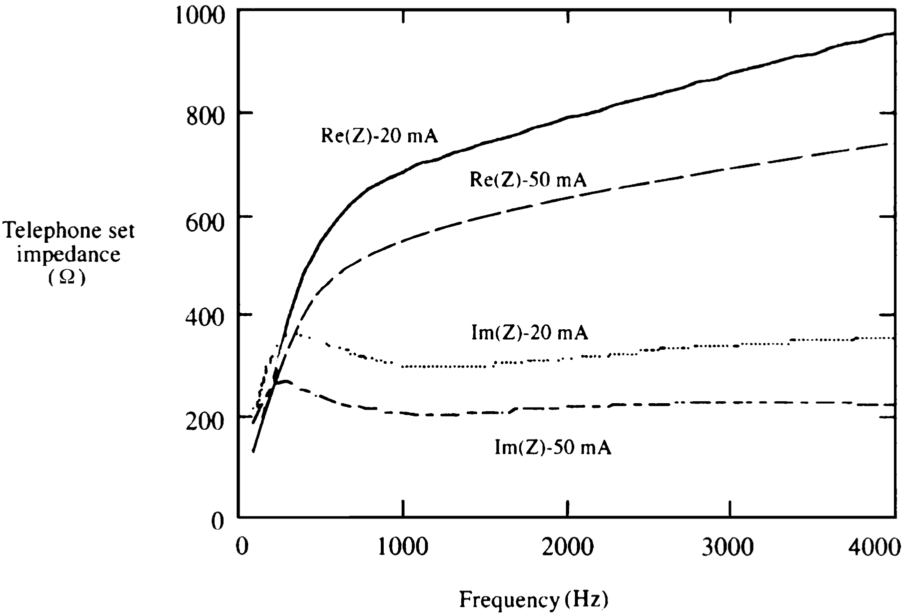


**FIGURE 17.3.10** Model for 500-type Telephone Set impedance at 20- and 50-mA loop current.

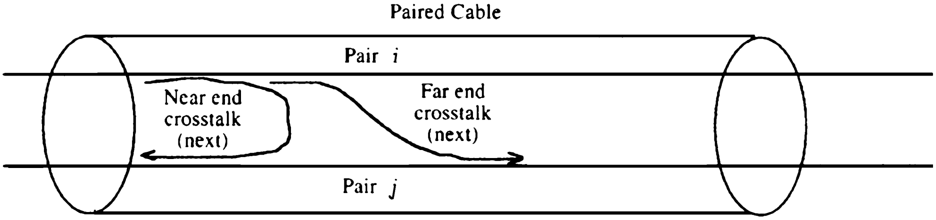


**FIGURE 17.3.11** Near-end and far-end crosstalk paths.

Adjacent pairs generally experience the lower crosstalk losses. Separation of directions of transmission to pairs in nonadjacent binder groups is a way to reduce crosstalk levels.

Near-end crosstalk is more important than FEXT in voice frequency circuits. If NEXT is excessive in such a circuit, the unwanted crosstalk signal may have sufficient power to be understood by a listener. This is known as *intelligible* crosstalk. This form of impairment is generally unacceptable in the local loop because the crosstalk loss between two loops is fixed by the physical proximity of the two pairs dedicated to the two loops and not a function of call connections as it is in interoffice trunks with random call-to-call crosstalk associations. The principal way to repair intelligible crosstalk in the loop is to move one of the affected parties to a different pair in a cable.

## Local Access Cable Organization

It is not practical to arrange loops terminating in a central office so that 100 percent of them would pass each home and business being served. Estimates must be made of the number of lines expected to be needed in each neighborhood or serving area to satisfy the expected demand for some time into the future. It has been especially important in the United States to have sufficient excess pairs available to any neighborhood to allow new service to be initiated within a day or two.

For many years telephone company engineers used a method called *multiple plant* to provide copper pairs to neighborhoods in a way that would be both flexible and economical. The use of multiple plant provides a *feeder* cable of a given number of pairs part way from a central office to a neighborhood. At a strategic point the cable is then spliced to two or more *distribution* cables that pass the homes and businesses to be served. Some of the pairs in multiple distribution cables are connected to the same feeder pairs, creating *bridged tap*. The voice frequency impairments due to the bridged tap are bounded by limiting the sum of the lengths of all bridged taps on a loop to less than 6000 ft. These impairments are traded for the flexibility needed to supply future circuits where the location of the potential demand is uncertain.

The long-term use of multiple plant caused some problems. Foremost among these was the need to open splices to rearrange pairs to provide more feeder pair capacity than originally planned to a distribution cable. Over long periods of time, the rearrangement activity caused damage to splices and corrupted cable records through accumulated errors. In the late 1960s, the serving area concept was developed to provide a more orderly and accessible method for connecting feeder cable pairs to distribution cable pairs.

The distribution cables are designed to have a capacity of up to two pairs dedicated to each living unit anticipated to exist in a neighborhood over a period of 20 or more years into the future. The number of pairs per ultimate living unit in distribution cables varies with telephone company local practice. Feeder cables to areas served by distribution cables are designed to have sufficient capacity for 5 to 7 years of anticipated demand and, therefore, have fewer pairs than the total numbers of pairs in the distribution cables being served. The feeder cables are terminated in an aboveground housing called serving area interface or, alternatively, feeder-distribution interface. The serving area interface also terminates all of the distribution cables that pass through the serving area and provides a cross-connection field to allow any feeder pair to be connected to any distribution pair using short pairs of wires called jumpers. Typically distribution areas have 600 or fewer living units and have distribution cables less than a mile in length. Distribution cables customarily are designed with 1.2 to two pairs per ultimate living unit. It is not uncommon for a serving area interface to terminate 600 feeder pairs and 1200 distribution pairs. Historically, about half of the capital investment in the local loop has been devoted to the feeder plant and half to the distribution plant. Figure 17.3.12 illustrates the multiple plant and serving area plant concepts.

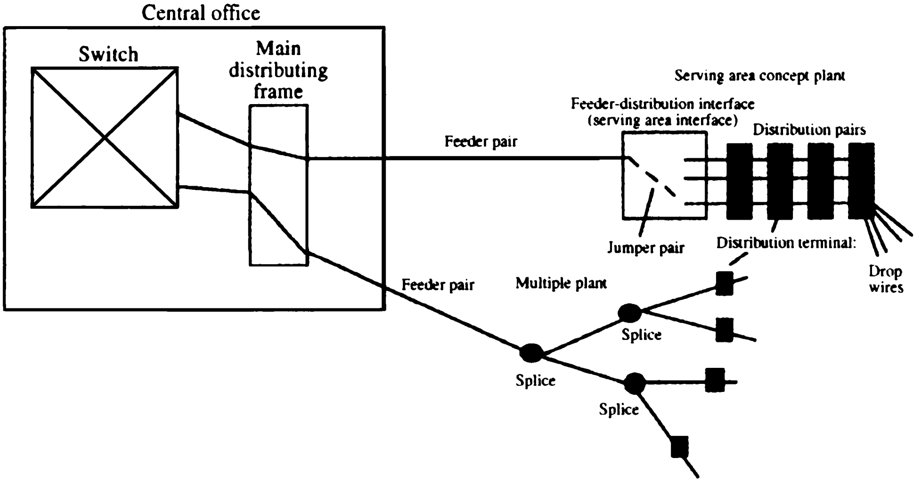


**FIGURE 17.3.12** Multiple plant and serving area concept designs.

## The Use of Electronics and Optics in the Local Loop

In the early 1920s electronic amplifiers began to be used in long-distance telephony. In the 1930s analog carrier systems were developed using frequency division multiplex techniques to carry multiple voice channels on a single-wire pair. These technologies were far too expensive to be used in the local loop, which continued to consist exclusively of wire pairs with those pairs longer than 18,000 using H88 loading to improve transmission.

After World War II, there was a surge of demand for telephone service that could not be met rapidly with added cables in the loop. This occasioned the examination of various electronic systems to allow a single-wire pair in the local loop to carry more than one conversation at a time. Early analog loop carrier systems, based on frequency division multiplex techniques that had been employed in telephone trunk transmission since the 1930s, were designed in the 1950s. Circuits based on the use of transistors, invented in 1947, were needed but the technology was immature. Systems cost too much and were not reliable enough to deploy widely.

By the late 1960s solid-state device technology was sufficiently economical and robust for application in the local loop. It became practical to build analog frequency division multiplex carrier systems for rural loop applications where the addition of a few circuits could obviate the construction of new cable plant. These systems typically carried six voice channels on a single pair of wires using frequency division duplex to achieve bidirectional operation with minimum NEXT. During that period it was found that investment in new cable construction for long rural loops could be reduced by employing voice frequency range extension electronics and finer gauge wires.

The principal of range extension is to aid the local switch in detecting telephone switch-hook transitions on loops of resistance higher than 1300 Ω and to amplify voice and tone signals to compensate for the added attenuation of the high-resistance loops. The amount of gain that may be inserted at the central office end of a loop is limited to 6 dB at 1 kHz to maintain the probability of encountering intelligible crosstalk at an acceptable level.

The use of a voice frequency amplifier with 6 dB of insertion gain allows loaded loops of up to 2800 Ω resistance to be used. Higher loop resistances are possible but, if transmission objectives of 8 dB insertion loss are to be maintained and crosstalk is to be acceptable, amplification is required at the customer premises end of the loop. Loop designs of up to 3600 Ω have been achieved with approximately 3 dB gain in the telephone handset. Deregulation of telephone sets by the FCC in 1976 made this option impractical, limiting the maximum copper loop resistance to 2800 Ω. A 2800-Ω loop resistance corresponds to about 82,000 ft of 22-gauge wire, a distance that reaches all but a small fraction of 1 percent of all loops. The 2800-Ω design virtually eliminated the need for 19-gauge cable in the loop, a 50 percent savings in copper.

T1 carrier line installation began in 1962. The T1 carrier line transmits digital signals at a rate of 1.544 Mb/s, capable of carrying simultaneously 24 pulse code modulated (PCM) voice channels at 64,000 b/s each. The T1 carrier signal contains a sequence of frames with 193 data bits each, 8 bits are assigned to each of the 24 information channels, and the remaining data bit is used to identify the start of a frame and for other, auxiliary purposes. A T1 carrier line requires two pairs of wires, one for each direction of transmission. Initial T1 line operation was devoted to interoffice trunk transmission. In 1972, the first digital loop carrier systems, employing T1 transmission, were introduced into commercial service. The first systems included a stage of switching concentration at each end of the T1 line, allowing up to 80 customer lines to share the 24-channel T1 facility with acceptable probability of blocking calls, depending on the offered traffic load.

In the mid-1970s digital loop carrier systems were introduced that used adaptive delta modulation techniques, taking advantage of knowledge of the dynamics of the human voice to reduce the data rate needed for satisfactory voice transmission to about 37,000 b/s. These systems enabled a T1 line to carry up to 40 simultaneous voice conversations with no blocking. Delta modulation was not compatible with PCM trunk transmission and gave way to the use of PCM in the next generation of loop carrier systems, the standard practice to the present time.

Digital loop carrier systems based on T1 lines are called "pair-gain" systems because they allow the simultaneous transmission of 24 voice signals, that would ordinarily require 24 pairs, on two pairs of wire thereby gaining the equivalent of 22 pairs. Early digital loop carrier systems were relatively expensive compared to wire pairs, depending on the length of the wire pair. Their use in the 1970s was largely confined to long rural loop cable routes. The value of digital loop carrier systems was the deferral of the construction of a new cable in an area of low demand for new lines. The savings due to the deferral of a major cable construction project for a few years more than offset the cost of purchasing and installing the carrier systems.

In 1979 the next generation of digital loop carrier systems was introduced using PCM at about the time of the introduction of digital local switching systems that also employed PCM transmission. These developments allowed the T1 lines from a digital loop carrier remote terminal to terminate directly on the switch without the need to convert the loop signals back to analog voice format at the switch interface. The efficiency of integrating digital loop carrier systems into the line side of digital switching systems added to the lower cost of manufacturing digital systems in the 1980s. These cost savings encouraged the routine use of digital loop carrier systems in conjunction with digital switches on much shorter than customary loop feeder cable routes in urban and suburban applications. By the mid-1980s over half of *new* loops were on digital loop carrier systems even though fewer than 10 percent of *all* loops were on digital loop carrier systems.

The density of loops increases exponentially as distance from the central office decreases. The cross-section of lines served by a digital loop carrier system remote terminal increases proportionately as they are installed on shorter loops. Typical digital loop carrier system remote terminals in the 1980s served from 96 to 544 lines each depending on the manufacturer. Typical high-density applications require more than 20 such terminals at a remote terminal location. It is not uncommon for digital loop carrier systems to be used on loops shorter than 2 mi.

Rural applications of digital loop carrier remote terminals require a cabinet of less than 30 $\text{ft}^3$ to serve 96 lines. Urban applications required underground vaults of over 1000 $\text{ft}^3$. The wide variety of applications of digital loop carrier remote terminals has required a large array of alternative enclosures to be deployed to meet local needs. Urban applications of digital loop carrier systems have also required a large variety of "special service" line interfaces to be supported in addition to the basic residential telephone line and coin line interface circuits.

Special services include private branch exchange analog and digital trunks, private line analog and digital data lines, foreign exchange two-wire and four-wire lines and trunks, and other specialized business services that have come to be offered over the years. These services each have specific transmission and signaling requirements to be met including the more stringent allocation of impairments to the local loop than is required for residential telephone service. Where special services are supported by copper pairs alone, signaling and transmission equipment has been installed in local central offices to compensate for the properties of wire loops in cables designed for residential service. This compensation has been designed into individual digital loop carrier plug-in "channel units" to enable telephone companies to provide special services through digital loop carrier systems.

The first trials of optical fiber in local loop transmission were conducted in the late 1970s. By the early 1980s the first commercial installations of digital loop carrier in association with optical fibers took place. The first digital loop carrier installation used multimode fibers with 50 or 62.5 $\mu$m core diameters. Multimode fiber was displaced by single-mode fiber by 1984, taking advantage of the superior cost and performance benefits of single-mode fibers. The type of single-mode fiber used typically has a core diameter of about 9 $\mu$m and is designed for minimum chromatic dispersion at an infrared wavelength of about 1300 nm.

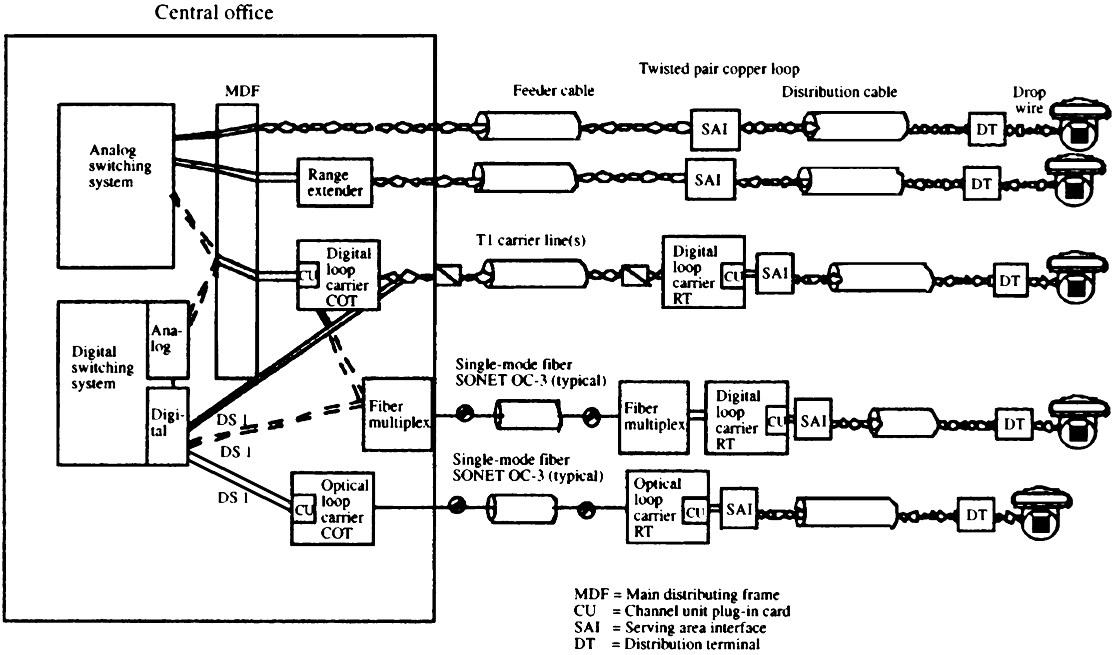


**FIGURE 17.3.13** Overview of range extension, digital carrier, and optical carrier systems.

Single-mode fiber transmission was at first at 45 Mb/s and higher while typical digital loop carrier systems were based on T1 lines at 1.544 Mb/s. The use of single-mode fiber required the addition of multiplexers that combined many T1 signals from multiple digital loop carrier systems into a higher rate digital signal suitable for transmission through fibers.

In 1988 the T1 Committee of the Exchange Carrier Standards Association published the first Synchronous Optical Network (SONET) rate and format standards, creating a standard, synchronous digital signal hierarchy with standard payload mappings suitable for transmission through single-mode optical fibers. It then became practical to design a digital loop carrier system that could connect directly to single-mode fibers, eliminating the need for separate multiplexers. The current generation of digital loop carrier systems is of this type. The most popular system can serve up to 2016 voice lines over four fibers (two operating fibers and two backup fibers) using the SONET OC-3 signal format at 155.52 Mb/s.

Figure 17.3.13 summarizes the generations of loop electronic systems that have been deployed from the late 1960s to the present time.

## *CABLE TELEVISION LOCAL ACCESS-LOOP DESIGN AND TECHNOLOGIES*

### Introduction

Beginning in the late 1940s community antenna television (CATV) companies were created to address the problem of weak signal strength from distant very high frequency (VHF) television broadcast stations. The 12 television channels of the day were assigned 6 MHz bands in the frequency space between 54 MHz and 216 MHz, skipping frequencies previously allocated for FM commercial radio and other applications. The over-the-air modulation plan is amplitude modulation with vestigial sideband (AM-VSB) transmission. Early CATV systems consisted of a head end and a distribution system. The head-end usually had a tower up to

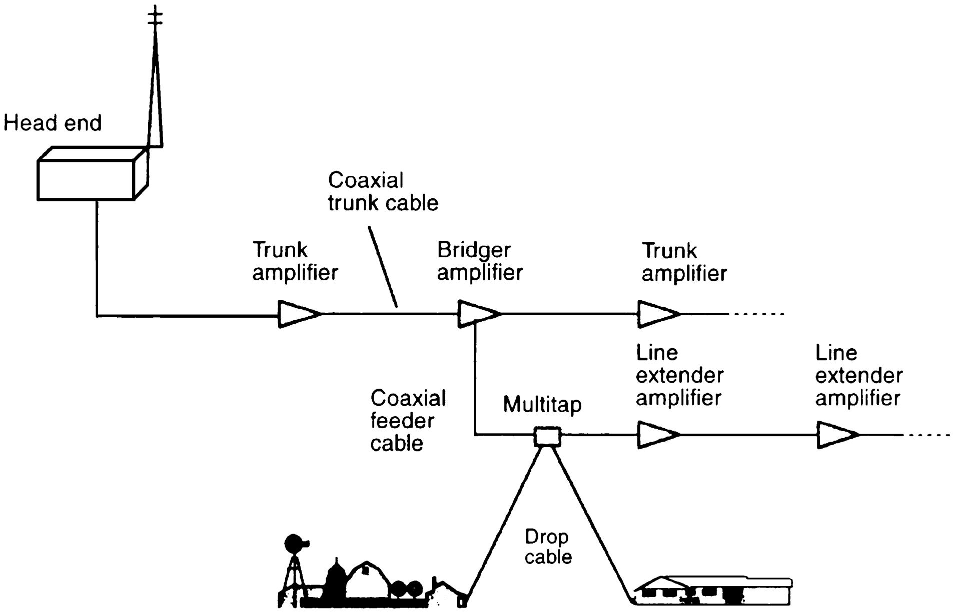


**FIGURE 17.3.14** CATV Local Access Network, all coaxial cable.

several hundreds of feet high at the outskirts of a community equipped with antennas aimed at distant transmitters. The distribution system carried a composite signal through trunk coaxial cables to the neighborhoods of homes to be served. Trunk amplifiers were placed at intervals along the cable route to compensate for signal attenuation and changes in attenuation versus frequency due to temperature fluctuations. The trunk cables were connected to feeder cables through bridging amplifiers. Customers were connected to feeder coaxial cables that passed their homes via in-line multitaps. The multitaps were connected to customers homes via coaxial drop cables that terminated at a grounding block at the side of the home for connection to inside coaxial cables terminated in television sets. As the CATV transmission system carried unaltered off-air signals, television set tuners could directly access the broadcast programs. By the mid-1960s the CATV local access distribution network architecture was well established as illustrated in Fig. 17.3.14. Many CATV systems carry FM radio signals as well as television signals, since the 88- to 108-MHz FM radio band is in the middle of the VHF television band.

In the 1970s, satellite transmissions of television signals to CATV head-ends became economical. C-Band satellites were the more common type using spectrum at 5.9 to 6.4 GHz for the uplink and at 3.7 to 4.2 GHz for the downlinks with capacity for 24 analog video channels. Each channel is served by a “transponder” in the satellite. Each channel occupies 36 MHz of bandwidth using frequency modulation. The addition of satellite antennas and receivers added considerably to the capital costs of headend electronics and suggested connecting more than one local distribution network to a single master headend. The links between local headends and distant “master” headends became known as “super-trunks.” Single-mode fiber optics came into use in the super trunk and trunk plant in 1984 and 1989, respectively. CATV systems now pass more than 90 percent of the homes in the United States and serve more than 60 percent.

There are three standard channel frequency assignment plans in use in CATV systems in the United States, as specified in FCC Bulletin 21006: (1) The standard (STD) plan, (2) the interval related carriers (IRC) plan, and (3) the harmonic related carriers (HRC) plan. The IRC and HRC plans lock the carrier frequency for each channel to a precision reference oscillator to reduce some of the second- and third-order harmonic distortion noise in the multiplexed CATV signal. Most systems use the STD plan. Newly installed commercial distribution systems now carry up to 110 channels in a band of frequencies up to 750 MHz.

Table 17.3.2 gives the frequency assignments up to channel 99 for the three plans.

**TABLE 17.3.2** CATV Channel Frequency Plans (MHz)

| Channel ID | STD plan | HRC plan | IRC plan |
|---|---|---|---|
| 2 | 55.25 | 54.0027 | 55.25 |
| 3 | 61.25 | 60.0030 | 61.25 |
| 4 | 67.25 | 66.0033 | 67.25 |
| 5 | 77.25 | 78.0039 | 79.25 |
| 6 | 83.25 | 84.0042 | 85.25 |
| 7 | 175.25 | 174.0087 | 175.25 |
| 8 | 181.25 | 180.0090 | 181.25 |
| 9 | 187.25 | 186.0093 | 187.25 |
| 10 | 193.25 | 192.0096 | 193.25 |
| 11 | 199.25 | 198.0099 | 199.25 |
| 12 | 205.25 | 204.0102 | 205.25 |
| 13 | 211.25 | 210.0105 | 211.25 |
| 14(A) | 121.2625 | 120.0060 | 121.2625 |
| 15(B) | 127.2625 | 126.0063 | 127.2625 |
| 16(C) | 133.2625 | 132.0066 | 133.2625 |
| 17(D) | 139.25 | 138.00669 | 139.25 |
| 18(E) | 145.25 | 144.0072 | 145.25 |
| 19(F) | 151.25 | 150.0075 | 151.25 |
| 20(G) | 157.25 | 156.0078 | 157.25 |
| 21(H) | 163.25 | 162.0081 | 163.25 |
| 22(I) | 169.25 | 168.0084 | 169.25 |
| 23(J) | 217.25 | 216.0108 | 217.25 |
| 24(K) | 223.25 | 222.0111 | 223.25 |
| 25(L) | 229.2625 | 228.0114 | 229.2625 |
| 26(M) | 235.2625 | 234.0017 | 235.2625 |
| 27(N) | 241.2625 | 240.0120 | 241.2625 |
| 28(O) | 247.2625 | 246.0123 | 247.2625 |
| 29(P) | 253.2625 | 228.0114 | 253.2625 |
| 30(Q) | 259.2625 | 258.0129 | 259.2625 |
| 31(R) | 265.2625 | 264.0132 | 265.2625 |
| 32(S) | 271.2625 | 270.0135 | 271.2625 |
| 33(T) | 277.2625 | 276.0138 | 277.2625 |
| 34(U) | 283.2625 | 282.0141 | 283.2625 |
| 35(V) | 289.2625 | 288.0144 | 289.2625 |
| 36(W) | 295.2625 | 294.0147 | 295.2625 |
| 37(AA) | 301.2625 | 300.0150 | 301.2625 |
| 38(BB) | 307.2625 | 306.0153 | 307.2625 |
| 39(CC) | 313.2625 | 312.0156 | 313.2625 |
| 40(DD) | 319.2625 | 318.0159 | 319.2625 |
| 41(EE) | 325.2625 | 324.0162 | 325.2625 |
| 42(FF) | 331.2750 | 330.0165 | 331.2750 |
| 43(GG) | 337.2625 | 336.0168 | 337.2625 |
| 44(HH) | 343.2625 | 342.0171 | 343.2625 |
| 45(II) | 349.2625 | 348.0174 | 349.2625 |
| 46(JJ) | 355.2625 | 354.0177 | 355.2625 |
| 47(KK) | 361.2625 | 360.0180 | 361.2625 |
| 48(LL) | 367.2625 | 366.0183 | 367.2625 |
| 49(MM) | 373.2625 | 372.0186 | 373.2625 |
| 50(NN) | 379.2625 | 378.0189 | 379.2625 |
| 51(OO) | 385.2625 | 384.0192 | 385.2625 |
| 52(PP) | 391.2625 | 390.0195 | 391.2625 |
| 53(QQ) | 397.2625 | 396.0198 | 397.2625 |

*(continued)*

**TABLE 17.3.2** CATV Channel Frequency Plans (MHz) (*Continued*)

| Channel ID | STD plan | HRC plan | IRC plan |
|---|---|---|---|
| 54(RR) | 403.25 | 402.0201 | 403.25 |
| 55(SS) | 409.25 | 408.0204 | 409.25 |
| 56(TT) | 415.25 | 414.0207 | 415.25 |
| 57(UU) | 421.25 | 420.0210 | 421.25 |
| 58(VV) | 427.25 | 426.0213 | 427.25 |
| 59(WW) | 433.25 | 432.0216 | 433.25 |
| 60(AAA) | 439.25 | 438.0219 | 439.25 |
| 61(BBB) | 445.25 | 444.0222 | 445.25 |
| 62(CCC) | 451.25 | 450.0225 | 451.25 |
| 63(DDD) | 457.25 | 456.0228 | 457.25 |
| 64(EEE) | 463.25 | 463.0231 | 463.25 |
| 65(FFF) | 469.25 | 468.0234 | 469.25 |
| 66(GGG) | 475.25 | 474.0237 | 475.25 |
| 67(HHH) | 481.25 | 480.0240 | 481.25 |
| 68(III) | 487.25 | 486.0243 | 487.25 |
| 69(JJJ) | 493.25 | 492.0246 | 493.25 |
| 70(KKK) | 499.25 | 498.0249 | 499.25 |
| 71(LLL) | 505.25 | 504.0252 | 505.25 |
| 72(MMM) | 511.25 | 510.0255 | 511.25 |
| 73(NNN) | 517.25 | 516.0258 | 517.25 |
| 74(OOO) | 523.25 | 522.0261 | 523.25 |
| 75(PPP) | 529.25 | 528.0264 | 529.25 |
| 76(QQQ) | 535.25 | 534.0267 | 535.25 |
| 77(RRR) | 541.25 | 540.0270 | 541.25 |
| 78(SSS) | 547.25 | 546.0273 | 547.25 |
| 79(TTT) | 553.25 | 552.0276 | 553.25 |
| 80(UUU) | 559.25 | 558.0279 | 559.25 |
| 81(VVV) | 565.25 | 564.0282 | 565.25 |
| 82(WWW) | 571.25 | 570.0285 | 571.25 |
| 83 | 577.25 | 576.0288 | 577.25 |
| 84 | 583.25 | 582.0291 | 583.25 |
| 85 | 589.25 | 588.0294 | 589.25 |
| 86 | 595.25 | 594.0297 | 595.25 |
| 87 | 601.25 | 600.0300 | 601.25 |
| 90(FM1) | 89.25 | NA | NA |
| 91(FM2) | 95.25 | NA | NA |
| 92(FM3) | 101.25 | NA | NA |
| 93(FM4) | 107.25 | NA | NA |
| 94(FM5) | 113.2750 | NA | NA |
| 95 | NA | 72.0036 | 73.25 |
| 96(A-5) | 91.25 | 90.0045 | 91.25 |
| 97(A-4) | 97.25 | 96.0048 | 97.25 |
| 98(A-3) | 103.25 | 102.0051 | 103.25 |
| 99(A-2) | 109.2750 | 108.0054 | 109.2750 |
| 1(A-1) | 115.2750 | 114.0057 | 115.2750 |

In 1972, the FCC required among other regulations that all CATV systems serving more than 500 subscribers be “two-way capable,” with a band of frequencies from 5 to 35 MHz being assigned to the reverse direction in a “subsplit” system. For many years this requirement was honored by installed trunk, bridging, and line amplifiers that included plug-in connectors for the attachment of diplex filters and reverse channel amplifiers to allow a system to be upgraded should the occasion arise. For the most part, this band has gone unused.

### CATV System Transmission Considerations

CATV system transmission suffers from the attenuation of signals through coaxial cables, the accumulation of thermal noise through a succession of amplifiers, the accumulation of second-order and third-order harmonic noise caused by nonlinearities in active and passive components, and the ingress of external interference.

Coaxial cable propagation constant and characteristic impedance may be written in the same form as for twisted pair transmission lines:

$$\Gamma = \sqrt{(G + i\omega C)(R + i\omega L)} \qquad \text{and} \qquad Z_c = \sqrt{\frac{(R + i\omega L)}{(G + i\omega C)}}$$

where $C = 2\pi\epsilon/(\ln b/a)$
$b$ = inside diameter of outer conductor
$a$ = outside diameter of the inner conductor

$G \sim 0$. $R$ and $L$ vary depending on the size and material of the inner and outer conductors.

The attenuation of a coaxial cable decreases with increasing diameter and increases with the square root of frequency. Typical trunk coaxial cables are 3/4-in. or 1-in. diameter with attenuation generally in the range of 1.0 to 1.5 dB/100 ft at 550 MHz. Feeder cables are similar in design to trunk cables but smaller in diameter, typically 1/2- to 5/8-in. diameter with attenuation in the range of 1.3 to 2.0 dB/100 ft at 550 MHz.

Trunk design typically allows about 20 dB loss between amplifiers creating spacings of 1400 to 2000 ft between trunk amplifiers at the high end of the frequency band supported by the system. Trunk amplifiers often include automatic gain and gain-slope adjustment capabilities to compensate for component aging and temperature variations. The carrier-to-noise (C/N) ratio is an industry metric for signal quality. C/N should be in excess of 46 dB. This limits the maximum number of amplifiers in tandem to less than about 20, thereby limiting the length of a distribution system. However, some applications may require a greater number of amplifiers because of the distance to be covered from the headend to the most distant customers, sacrificing noise performance.

The feeder cable design must compensate for the loss of multitaps as well as the feeder cable. Line extender amplifiers are usually limited to about three in cascade and are set for 25 to 30 dB of gain. The line extender amplifiers contribute significantly to harmonic distortion in the signal because they operate at high output levels. Composite second (CS) order and composite triple beat (CTB) are metrics governing signal distortion. Each is maintained at less than –53 dBc (dB with respect to carrier power) in a well-designed system.

Subscriber drop cables are typically braided outer conductor coaxial cables with attenuation as high as 15 dB. Almost half of the total length of coaxial cable in a distribution system is composed of drop cables. The most common drop cables are RG-59 and RG-6 equivalent types.

The drop cable is connected to the feeder cable through a passive component called a multitap. Multitaps contain directional coupler circuitry with two, four, or eight drop cable connections. The attenuation toward the subscriber is fixed and is selected by the engineer/designer of the plant to match the signal level at that point along a feeder cable so that the subscriber signal level will be as close to the desired 0 dBmv level as possible. The reverse direction from the customer experiences greater attenuation to limit the interference that is transmitted back toward the headend from the subscriber's equipment.

Customer wiring may be customer-installed or CATV company-installed RG-59 coaxial cable with passive splitters to allow service to branch to different rooms in a home. In-home cables terminate either directly on television sets or VCRs or on set-top converters supplied by the CATV company. CATV services are categorized as basic, premium, and pay-per-view. Premium and pay-per-view signals are encrypted by the CATV service provider and require a set-top converter to decipher the signal. In the case of pay-per-view services, the set-top converter is addressable by the CATV provider and is instructed to decipher signals on request of individual subscribers. Basic services may be viewed without the aid of the set-top converter by television sets and through VCRs with tuner circuits designed to correctly interpret the standard, IRC, and HRC channel formats. Appliances that can do this are called cable-ready.

CATV distribution systems are powered by distributed in-line 60-V, 60-Hz supplies connected to public utility power distribution networks. CATV power supplies feed ac current over the coaxial cables in both directions from the location of the supply. As much as 10 A may be passed through the cables and associated amplifiers. Set-top converters are powered by the subscriber.

The total costs, including labor and materials of a coaxial cable distribution system, consist of about 38 percent for coaxial cable, 24 percent for electronics, 20 percent for physical hardware, and 18 percent for passive components.

## The Use of Fiber Optics in CATV Distribution Systems

The use of single-mode optical fibers in CATV trunk plant has advanced very rapidly with advances in the design of laser transmitters and optical receivers capable of the linearity required to satisfactorily carry the CATV amplitude-modulated, frequency-multiplexed extremely wide bandwidth signals. The use of optical fiber trunk plant benefit the CATV operator in three ways: (1) It reduces the number of amplifiers in cascade between the headend and the subscribers, improving system performance; (2) it improves the reliability of the distribution system by eliminating many active elements; and (3) it moves the bandwidth constraint on the trunk plant to the ends of the fibers, requiring simpler engineering to upgrade the plant to greater bandwidths. Laser transmitter and optical receivers are commercially available to carry more than 100 channels in a 700-MHz bandwidth from 50 to 750 MHz on a single fiber.

Early CATV applications of optical fibers used Fabry-Perot lasers that lacked the linearity to carry amplitude modulated signals. Modern CATV trunk systems mainly use distributed feedback (DFB) lasers that exhibit superior linearity of operation. The lasers are sensitive to reflected signals from splices and connectors. Typical transmitters include an optical isolator between the laser and the trunk fiber to block reflections coming back toward the laser. DFB laser transmitters are relatively expensive but costs have been reduced to allow an optical transmitter to be dedicated to clusters of as few as 2000 homes. Optical couplers may be used to allow a laser transmitter to be shared by two to four trunk fibers. Figure 17.3.15 illustrates the use of optical fiber in a CATV distribution system trunk application. This arrangement of fiber trunks and coaxial feeder cables is commonly referred to as Hybrid Fiber-Coaxial or HFC plant.

The remote optical node or, simply, remote node that terminates the fiber at the end of the trunk plant typically contains a receiver using a *pin* photo diode detector. The remote node may contain amplifiers capable of

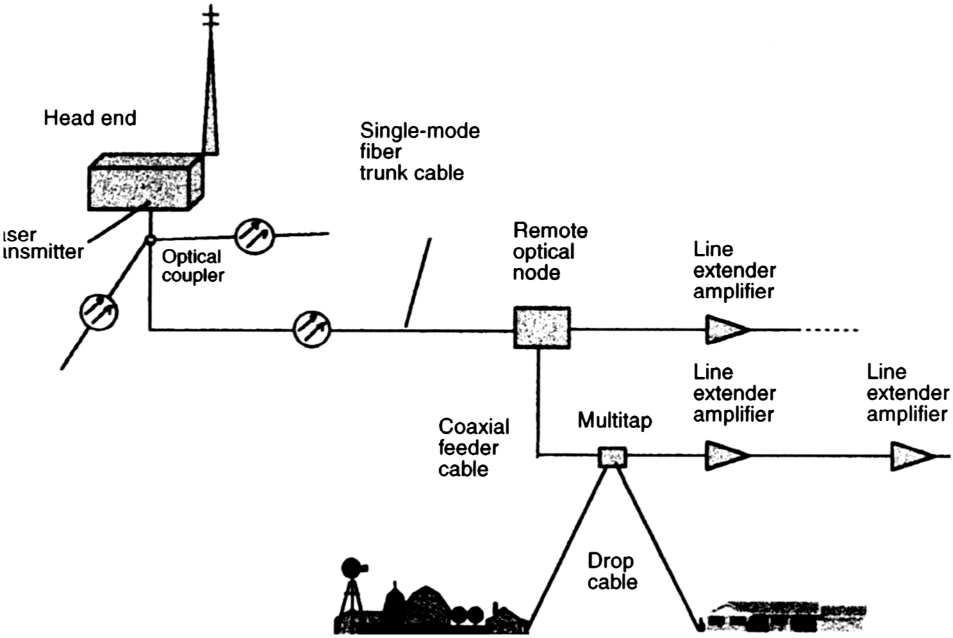


**FIGURE 17.3.15** Cable television local access with optical fiber trunk.

serving up to four feeder cables. The attenuation of the optical signal between the laser transmitter and a remote node is commonly in the 10- to 12-dB range. If a coupler is used, over half of the allocated optical loss budget will be consumed by the coupler.

## EMERGING TRENDS IN TELEPHONE AND CATV LOCAL ACCESS

### New Technologies for Wire Pair Transmission

In the early 1990s, developments in integrated circuit technology have enabled digitally encoded signal formats to be defined that make more efficient use of the available frequency spectrum for wire pair transmission. As a group, these techniques are referred to as *digital subscriber line* (DSL) technologies. The first of the standard DSLs to employ full duplex transmission over a single-wire pair in the United States is the integrated services digital network (ISDN) basic rate access transmission line that enables the bidirectional transmission of 160 kb/s over nonloaded pairs over 18,000 ft in length. The ISDN basic rate access line uses a multilevel line code referred to as 2B1Q for two binary, one quaternary. The 2B1Q line code places 4 bits of information in each pulse by using four pulse amplitudes, two positive and two negative. Complex echo cancellation and signal equalization techniques are used to compensate for bridged tap and impedance discontinuity impairments.

More recently, the 2B1Q encoding has been extended to allow bidirectional signals with data rates of 784 kb/s to be transmitted over twisted pairs meeting Resistance Design criteria to a distance of 12,000 ft. This technique is referred to as high bit rate digital subscriber line or HDSL. By using HDSL, telephone companies can provide services requiring T1 data rates over two pairs that are twice as long as the spacing between regenerators on T1 carrier lines and require no conditioning, i.e., removal of bridged tap, or complex design procedures.

Another technology that has been developed recently is the asymmetric digital subscriber line (ADSL) using digital modulation and frequency division multiplexing to transport high data rate digital signals over unconditioned twisted pairs. Early modulation techniques used include discrete multitone (DMT) and carrierless amplitude and phase modulation (CAP). Transmission is asymmetric over a single twisted pair to support the possible delivery of compressed, digital video signals to residential consumers. Experimental systems offer up to 6 Mb/s transmission toward the customer with up to 640 kb/s in the reverse direction over loops up to 12,000 ft in length. There is promise that ADSL techniques may allow the transmission of signals up to 52 Mb/s data rate over much shorter, but useful distances.

### Digital Video Services over Fiber and Coaxial Cables

Telephone companies have been experimenting with “fiber-to-the-curb” systems since 1988. These systems are based on the technology of digital loop carrier systems but extend optical fibers into the telephone distribution plant. There have been limited commercial deployments of systems that followed requirements in Bellcore Technical Reference (IR) TSY-000909. To date the cost of purchasing and installing FTTC systems has been too high to allow economical mass deployment for switched and private line telephone services in this way.

TR-909 compliant FTTC systems consist of a host digital terminal (HDT), a fiber distribution system, and optical network units (ONU). The HDT provides the connections to the local telephone switch, private lines that do not terminate on the switch, and network management systems. The HDT may be located in the central office or at a remote terminal site distant from the central office. ONUs provide the service interface circuits for connection to the end users and test and maintenance circuits to allow remote testing to be done on the drop wire connection to the home from a centralized maintenance system.

The distribution connection from the ONU may be a simple point-to-point time division multiplex arrangement or, alternatively, a point-to-multipoint arrangement having more than one ONU sharing the optical interface at the HDT. Point-to-multipoint connections may use a variety of multiple access protocols. Most common to date are time division multiple access (TDMA) systems that broadcast the same time division multiplex signal to all ONUs but receive signals from each ONU in turn, allowing multiple ONUs to share the single HDT optical receiver and transmitter. Figure 17.3.16 illustrates one form of FTTC connections with tandem HDTs that are located in the outside plant as well as in the central office. The HDT may also serve the function of an optical loop carrier terminal in this example, remote or central office, since all

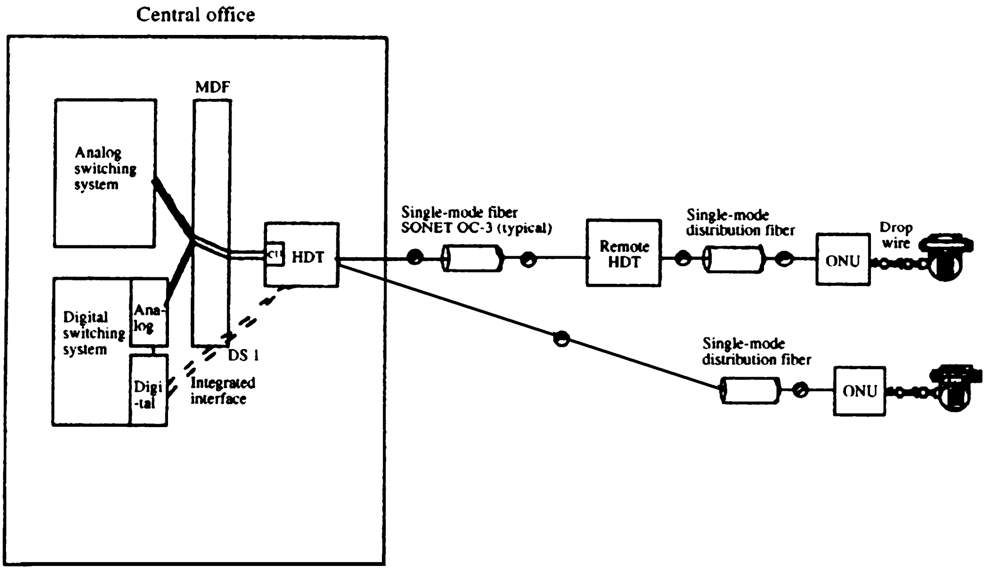


**FIGURE 17.3.16** Telephone fiber-to-the-curb example.

of the service, switch, maintenance, and network management interfaces are the same. This may be accomplished if the optical loop carrier system has an architecture that enables the provision of optical distribution interfaces to ONUs as well as twisted pair distribution interfaces to end users. Otherwise, the remote HDT must be connected to a digital switch via a pair of back-to-back fiber multiplexers and to an analog switch via a pair of multiplexers and a digital loop carrier COT.

The telephone local access challenges have increased since the FCC Video Dial Tone order, issued in June 1992. After lengthy deliberations, the FCC reaffirmed the order in November 1994 and has since begun approving telephone company Section 214 construction applications. Video digital tone is regarded as a common carrier video services delivery service that telephone companies may provide. Heretofore, telephone companies have been restrained from providing cable television services and have not been allowed to own cable television companies in their franchise territories.

After considerable study, telephone companies have arrived at different conclusions regarding the best combination of technologies to use for video dial tone services. If these services are to include multicast analog video channels such as the local broadcast stations, then hybrid fiber-coaxial plant is considered to be the most economical approach. Some companies have decided to replace their telephone loop plant with HFC plant for video dial tone applications and have decided to include telephony services to be transported over the same plant.

This has stimulated a number of equipment suppliers to begin the development of systems that drive telephone services over HFC plant, illustrated in Fig. 17.3.17. Although not absolutely required, most systems in development use a second fiber from the HDT in the central office for the return or upstream direction of transmission. The application of telephony to HFC plant significantly increases the reliability requirements of the plant. In particular power supplies must be equipped with 8 h of battery reserve operation in the event of power failures in a neighborhood in order to provide telephone service of comparable reliability to existing wireline services.

Adding telephony services requires that coaxial termination units that derive the telephony service interfaces, much like those in optical network units and digital loop carrier systems, must be installed at or near subscriber homes. The coaxial termination units communicate toward the HDT using frequencies under the downstream 50 MHz lower bound for subsplit systems. Emerging systems are carrying the upstream telephony signals in the range of approximately 15 to 40 MHz using various modulation and multiplexing designs to maximize the efficiency of use of the limited spectrum. Some systems incorporate frequency shifting circuitry to avoid, as needed, the significant levels of ingress noise found in the lower frequencies of the upstream band. Some systems also assign digital channels on demand for added efficiency rather than dedicating upstream

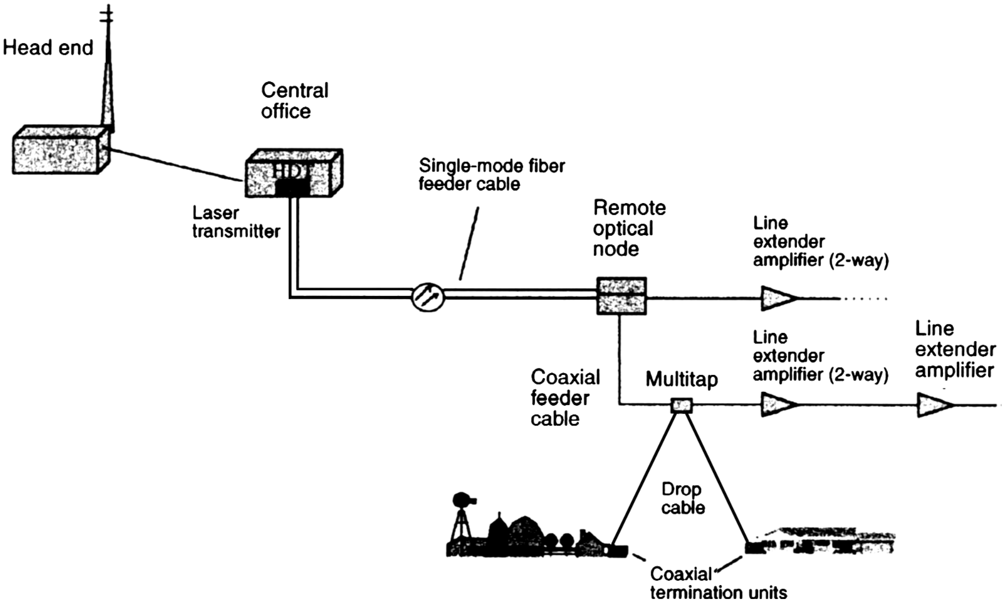


**FIGURE 17.3.17** Hybrid fiber-coaxial plant with video and telephony capabilities.

channels full time to customer lines. CATV system operators, interested in providing alternate local telephone access, are also likely to employ such systems to derive telephony services over HFC plant.

Great strides have been made in the development of algorithms for reducing the amount of data required to carry television signals in digital form. Standards for these techniques have been drafted by the International Standards Organization Motion Picture Experts Group (MPEG). The emerging standards are referred to as MPEG1 and MPEG2. These algorithms take advantage of the frame-to-frame redundancy in motion pictures and television signals to remove more than 90 percent to the data contained in digitally encoded versions of the material. The MPEG1 standard was developed primarily for CD-ROM applications that allow fixed data transfer rates of up to about 1.5 Mb/s but has been extended to provide higher quality signals at higher data rates for satellite and potential CATV distribution. MPEG2 incorporates a packet transport protocol that allows the multiplexing of multiple images in a single data stream and supports variable data rate encodings. The MPEG standards are asymmetric, favoring simple decoding and complex encoding processes in support of unidirectional transmission.

MPEG encoding of video, coupled with efficient digital signal modulation techniques such as quadrature amplitude modulation (QAM) allows several video signals to be carried in the 6 MHz channel space of a single analog video signal. The number of compressed, digital signals that can be carried in a channel can be 10 or more and is a function of the compression ratio achieved for a given level of quality and the modulation method chosen. With MPEG and digital modulation a modern CATV distribution system can carry many hundreds of programs simultaneously.

Advances have also been achieved in the area of Asynchronous Transfer Mode (ATM) standards that allow the flexible multiplexing of voice, video, and data signals together despite great disparities in the data rates of the individual signals. ATM standards support the mapping of signals into fixed length packets, 53 bytes in length, called cells, that can be transported and switched readily through high-speed optical transmission lines. The SONET standards include a payload mapping to support the transport of ATM signals through the SONET digital signal hierarchy. It is believed by many that video dial tone networks will rely on ATM-based switches to allow end users to call up digitally compressed video program material on demand from archives of material.

Both hybrid fiber-coaxial and fiber-to-the-curb access networks can support the transmission of digitally compressed video signals, multicast and switched on demand. The latter part of the 1990s will witness a great upheaval in local access networks as CATV companies and telephone companies race to modernize their local access plant to support compressed, digital video service offerings. In the process they will discover the technological approaches that are most suitable and economical for the purpose. The Telecommunications Act of 1996 has caused the FCC to order telephone companies to unbundle their local access networks to support facility-based local access competition. This will add regulatory and competitive uncertainties, perhaps retarding the introduction of new technology.