Chapter 1

CABLES: A CHRONOLOGICAL PERSPECTIVE

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He, who does not know his past,
remains forever a child.
Cicero

1.1 PRELIMINARY REMARKS

Metallic conductor cable technology is perhaps one of the oldest fields of endeavor in electrical engineering, whose origins can be traced back approximately 150 years. Not far behind on the chronological scale are situated the dielectric medium cables, which had their seminal beginnings more than 100 years ago in the early studies of light ray transmission along pipes that culminated in the 1960s with the development of optical fiber cables. Although current cables represent a vast improvement over their predecessors, they have changed very little in their fundamental design. Thus, in metallic conductor cables, the conductor along which the power and signals are transmitted must be kept isolated and insulated from its surroundings by a dielectric layer, and in an optical dielectric conductor cable, the guided light signal must remain confined within a fiber core or dielectric channel by means of a light-reflecting enclosure or cladding. The cable characteristics are determined by the geometrical parameters of the cable such as metallic conductor radius, insulation thickness, optical fiber core diameter, etc., as well as the electrical and physical properties of the materials constituting these and other component parts of the cables. Since the geometrical parameters of cables are generally optimized, amelioration of any given cable design is controlled by the improvements effected in either existing cable construction materials or the availability of new materials with outstanding properties and processability. Consequently, cable technology by its very nature is essentially a materials-based technology. In this chapter, we shall follow the chronological evolution of power and communication cables and delineate the past causes and events that have led to the mutations of the two main generic categories of cable currently in use.

The development of early power cables can be said to have followed closely the extension of the cable techniques, which had been developed on low-current cables, lines for telegraphy, and explosive mine cables. In fact, in the incipient stages of their development, both power and metallic conductor communication cables were evolving with considerable similarity. Steel conductors were being replaced with copper, and the early insulation consisted of gutta-percha, rubber, or various impregnated systems. The cable installation techniques employed were also alike in many respects.

As power transmission and distribution was carried out at direct current (dc) or low frequencies (25, 50, or 60 Hz) but at high voltages, while that of voice information was transmitted at low voltages but at high frequencies, it was a natural consequence that differences between the two systems would become increasingly more apparent in time. Even at the relatively lower values of transmission frequency employed in the early telephone cables, the cables were usually long in comparison to the wavelength of the signal transmitted in contrast to the power cables, which were electrically short lines vis-à-vis the wavelength of the power frequency. Since in power systems the power supplied to the load was obtained commonly from the same circuit, the tendency was, therefore, toward interconnection and development of large systems comprising a relatively small number of large power generating units. With telephone systems, it was, however, necessary to maintain an independent channel of communication for each pair of communicators or talkers. Evidently, this enabled a small amount of copper to provide a relatively large number of circuits either by the use of many small-diameter conductors or by the superposition of a number of independent channels of communication on a single pair of wires [1]. The transmitted acoustic power was minuscule at the relatively low voltage employed; accordingly, not only the conductor size but also the insulation thickness required were small. The important considerations in communication cables centered on the need for low attenuation and speech distortion and negligible cross talk between adjacent circuits. To meet these requirements, the cables were to have low losses at the operating frequencies, with low capacitance per unit length and low mutual capacitance between adjacent twisted-wire pairs. These constraints differed greatly from those imposed on power transmission and distribution cables. Power cables were to transmit sizable blocks of power and, as a consequence, had to be operated at high voltages with large current flows in their conductors. Hence, the size of the conductor was to be sufficiently large to carry the necessary load current without overheating and limiting the voltage drop per unit length; also, the insulation thickness and its dielectric strength were to be sufficiently great to withstand the high operating voltage gradients or stresses. The capacitance per unit length was to be low to limit the capacitative charging currents; the dielectric losses were also to be small, particularly if the cables were to operate at the more elevated voltages. Thus, voltage and temperature became the preponderant parameters in the rating of power cables.

Notwithstanding the salient differences between power and metallic conductor communication cables, certain inherent similarities did nevertheless prevail. Many of the materials used on the two types of cables were identical. Certain manufacturing processes and techniques were the same. For example, the same sheathing and armoring could be applied equally well on both telephone and power cables. The larger diameter conductors used on some power cables were obtained simply by stranding the smaller conductors that could be used on certain communication cables. It is thus not surprising that the basic similarities in the construction and manufacture of power and metallic conductor communication cables were sufficient to allow most cable manufacturers to produce both types of cable. It is only with the introduction of optical fiber communication cables, whereby information became transmitted along dielectric conductors in lieu of the metallic wires, that there occurred a major bifurcation in cable manufacturing techniques. The silica fibers had to be drawn under highly controlled conditions to prevent contamination effects and ensure accurate diameter control, which was in the order of a fraction of a micrometer. In addition, a well-controlled layer of cladding material was required over the optical fiber core to impart the desired lightwave guiding characteristics to the optical transmission line. However, the remaining manufacturing steps resembled closely or were identical to those common to conventional metallic conductor cables. The cladded optical fibers were protected by extruded polymeric coatings and placed loosely within tubes of polymeric material or in a polymeric buffered structure containing strength members (steel or polymer) to provide mechanical protection. The jackets on the optical fiber cables were similar to those on metallic conductor communication cables. Metallic shielding was employed primarily to avert rodent damage, as opposed to metallic conductor communication cables where metallic coverings were in addition desirable for electromagnetic shielding, particularly as concerns surges, arcing from lightning, and adjacent power lines or cables.

In some applications, composite or hybrid cables were used, necessitating the cable engineer to have some familiarity with both metallic and optical communication cables as well as power cables. For example, certain optical fiber cables contained metallic conductor twisted-wire pair communication lines that are required for control purposes. The immunity of optical fiber cables to electromagnetic interference rendered them particularly suitable for deployment in conjunction with power cables either along the grounded shield of power cables or incorporated as a part of grounded conductors. In addition, there has been a considerable increase in the use of the same rights-of-way for both power and communication cables. In such circumstances, when copper conductor communication cables were employed, they had to be adequately shielded by metallic shields to be protected against ground faults that may originate from adjacent power cables.

1.2 POWER CABLES

Power cable technology had its beginnings in the 1880s when the need for power distribution cables became pressing, following the introduction of incandescent lighting. With urban growth, it became moreover increasingly necessary to replace some of the overhead lines for power transmission and distribution with underground cables. The illumination of the larger cities proceeded at such a rapid pace that under some circumstances it was impossible to accommodate the number and size of feeders required for distribution, using the overhead line system approach. In fact, this situation deteriorated so notably in New York City that, in addition to the technical and aesthetic considerations, the overhead line system began to pose a safety hazard to the lineworkers themselves, the firemen, and the public. As a result, the city passed an ordinance law in 1884 requiring the removal of the overhead line structures and the replacement of these with underground cables [2]. Similar laws and public pressure were applied in other cities, with the consequence that by the early 1900s, underground electrification via insulated cables was on its way to becoming a well-established practice.

A practical lead press was invented in 1879 and subsequently employed to manufacture 2-kV cables for Vienna in 1885 [3]. During the same period vulcanized rubber was used to produce cables on a commercial scale, although use of gutta-percha had already been made as early as 1846. Impregnated-paper power cables were first put on the market in 1894 by Callender Cables of England, using impregnant mixtures of rosin oil, rosin, and castor oil; only in 1918 were these replaced by mineral oils [3]. In North America impregnated-paper cables were first supplied by the Norwich Wire Company. Varnished cambric cables were introduced by the General Electric Company in 1902;

the high-temperature behavior of these cables was subsequently improved in 1910 by the addition of black asphalt.

It is interesting to note that some of the earliest power cables consisted merely of ducts with the copper conductors insulated from ground by glass or porcelain insulators. In fact, in 1889 the entire city of Paris was electrified using this scheme with sewers serving as ducts. Some of the more common early solid and liquid insulating materials employed in various underground cable installations were natural rubber, gutta-percha, oil and wax, rosin and asphalt, jute, hemp, and cotton. In 1890 Ferranti developed the first oil-impregnated-paper power cable; following their manufacture, his cables were installed in London in 1891 for 10-kV operation. It is most noteworthy that the cables had to be made in 20-ft lengths; as the total circuit was 30 miles in length, about 8000 splicing joints were required. Nevertheless, these cables performed so well that the last cable length was removed from service only in 1933. In 1892, Buffalo, New York, was illuminated with arc lamps, and for this purpose 7.5-kV rubber insulated cables of the concentric design, using an overall insulation thickness of $\frac{1}{8}$ in. were placed in service [4].

Cable installation continued to proceed at a rapid pace, so that by the turn of the century many major cities throughout the world had many miles of underground power cable. For example, already by the end of 1909, the Commonwealth Edison Company in Chicago had 400 miles of underground cable operated in the voltage range from 9 to 20 kV. Montreal had some 4500-ft circuits of three-conductor cables installed in ducts under the Lachine canal for 25-kV operation; the same voltage was used for cables traversing the St. Lawrence River in 1906. With some experience behind them, cable manufacturers were increasingly gaining confidence and during the St. Louis Exposition in 1904 power cables developed for voltages as high as 50 kV were put on display [4].

1.2.1 Oil-Impregnated Paper Power Cables

During the period prior to World War I, extensive use was made of oil-impregnated paper cables of the three-conductor belted type for voltages up to 25 kV. This antiquated design is illustrated in Fig. 1.1 [5]. Due to the nonuniform stress distribution in the cable construction, the belted cable proved to be highly partial-discharge susceptible when attempts were made to extend the operating voltage range with larger wall thicknesses to approximately 35 kV, to meet the increased power demand following World War I [4]. This problem was resolved by shielding the individual conductors, using 3-mil-thick copper tapes. The outside of the shielded conductors was thus maintained at the same ground potential. In addition, the belt insulation was replaced with a

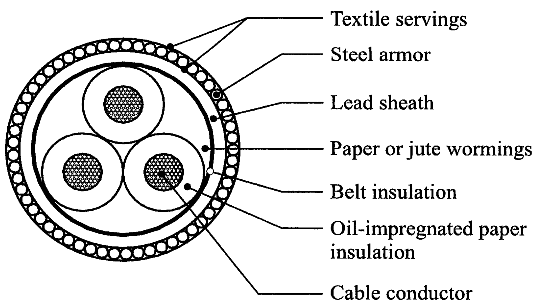


Figure 1.1 Cross section of unshielded three-conductor belted-type high-viscosity oil-impregnated paper power cable.

binder consisting of fabric tapes and strands of interwoven copper wire. The purpose of the latter was again to maintain the shields of the three cables at the same potential (ground). Over the years, the conductor shapes of the three-conductor shielded paper insulated cables have evolved into three forms, namely circular, oval, and sectoral (cf. Fig. 1.2). In many utilities a substantial portion of the present-day distribution load is still carried at 35 kV via three-phase oil-impregnated paper belted cables, with the three conductors individually grounded. There is little inducement to replace these cables with solid extruded dielectric cables, whose outer diameter for an equivalent power rating would exceed that of the ducts accommodating the more compact three-phase oil-paper belted cables. Moreover, the oil-paper belted cables have been characterized by remarkably long in-service lifetimes that often exceed 65 years. Belted cables with unshielded conductors are still deployed but only for working voltages equal to or less than 15 kV.

With the individual conductors shielded, it was possible to extend the use of the three-phase belted cables for voltages as high as 69 kV, though on the average their application has been confined to voltages below 35 kV. The main reason for this upper limit has again been associated with the occurrence of partial discharges, which had in numerous instances led to the deterioration and failure of the dielectric at the elevated voltages. The partial discharges were found to take place in voids, which were formed either during the manufacturing process or during the load cycling while in service.

1.2.2 Oil-Pressurized Power Transmission Cables

The problem with void-associated discharges at the higher values of applied voltage, required for the transmission of electrical energy, was finally and effectively eliminated by the introduction of a low-viscosity oil-impregnated-paper insulating system; in this scheme, the formation of cavities was avoided by maintaining a pressure slightly above atmospheric on the insulating oil. The principle of this oil-filled-paper power cable was first expounded by Emanueli in 1917 and, in its original concept, the cable consisted of an oil-impregnated-paper insulation applied over a conductor strand, having a hollow center filled with oil (cf. Fig. 1.3). The first installation of a single conductor oil-filled cable rated at 66 kV was made in England in 1928; this was followed in 1931 with a 132-kV design installation. However, the first oil-filled cables installed on an actual system were those in Chicago and New York, in which use was made of a gravity feed of a minimum pressure of 1 lb/in.^{2}, which was just sufficient to prevent ingress of air and moisture.

Emanueli's design was based on the principle that the heated oil in the cable must be allowed to expand during the load cycle into an oil reservoir connected at its upper end; upon removal of the load, the oil is thus free to return or contract into the cable [6]. Present-day oil-filled cables differ very little in principle from Emanueli's early design, though higher oil or dielectric liquid pressures are employed

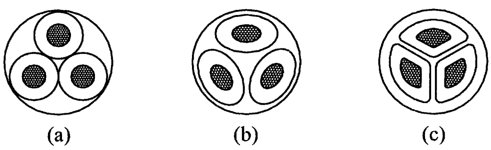


Figure 1.2 Configurations of shielded three-conductor belted-type high-viscosity oil-impregnated paper power cables: (a) round, (b) oval, and (c) sectoral conductors.

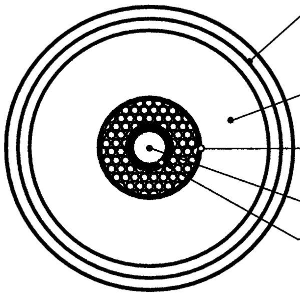


Figure 1.3 Emanueli oil-filled hollow-conductor power cable.

and the reservoir tanks generally make use of pressurized air cells. The oil in the hollow-core oil-filled cables can be maintained under pressure by means of pressurized oil tanks at the ends of the cable. In other types of pressurized cables, pressure in the insulation may be maintained by gas pressure applied either to the lead sheath, which acts as a flexible membrane, or directly to the solid-liquid dielectric. Static oil pressures up to 75 lb/in.^2 are common. The minimum permissible oil pressure is about 10 lb/in.^2; at the other extreme, pressures as high as 450 lb/in.^2 may be required due to vertical rises in the cable layout such as in the case of the Churchill Falls cables. With the majority of dielectric liquid or oil-filled cables, the maximum permissible stresses at the conductor may vary usually between 90 and 150 kV/cm; while with the so-called solid-type higher viscosity oil-impregnated paper insulated lead-covered (PILC) power cables, the equivalent stresses range below 40 kV/cm. Over the past decades, the operating voltages of oil-filled cables have been increasing steadily. In 1957, 14 circuit miles of 238-kV, oil-filled cable (insulation thickness of 0.835 in.) were installed in British Columbia; another 300-kV installation was made at Kitimat in the same province. An oil-filled cable system voltage of 230 kV is now common for underground power transmission in most of the larger Canadian cities. In the Montreal area, an oil-filled cable system voltage of 315 kV has been in effect since 1982. Throughout the world, a few oil-filled cable installations have been made for extra-high-voltage (EHV) levels up to 500 kV; most noteworthy is the 525-kV self-contained oil-filled cable system at the Grand Coulee Dam, Washington State [7]. The latter cable has a nominal insulation wall thickness of 30.5 mm, an aluminum sheath of 4.6 mm thickness, and a polyvinyl chloride (PVC) jacket of 3.1 mm thickness. Metallized carbon papers were used for shielding, and a copper conductor of 40.0 mm diameter formed the inner hollow core. The cable was designed to operate at a maximum oil pressure of $2.25 \times 103\,\text{kN/m}^2$ and a dielectric loss of 17.4 W/m as compared to 12.8 and 7.2 W/m for the conductor and sheath, respectively. It is interesting to note that in recent years this particular cable had experienced failure. Attempts have been made to extend the self-contained dielectric liquid or oil-filled cable design up to voltages of 750 kV and beyond, using impregnated paper as the insulant. In such cable designs maximum stresses of 210 kV/cm are contemplated; as these cables are to carry loads greater than 2 GVA, the cable systems, due to their relatively high power losses, would require other than only natural cooling. A cross section of a possible 750-kV cable design, using an internal oil pressure of 15 atm, is delineated in Fig. 1.4 [8].

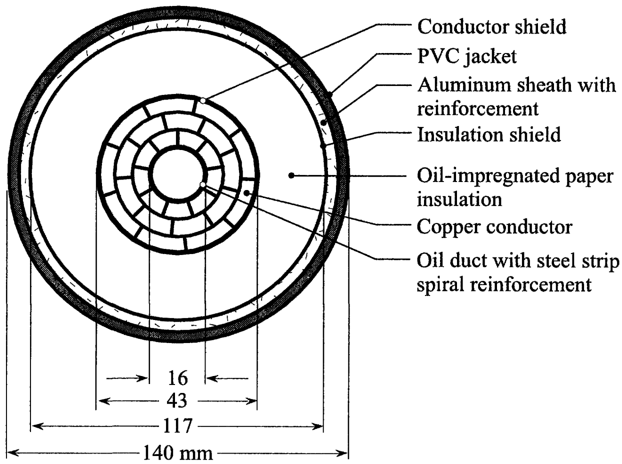


Figure 1.4 Cross section of 750-kV oil-impregnated paper self-contained oil-filled power cable with copper conductor cross-sectional area of 1100 mm^2 (after [8]).

In North America commencing with 1932, the first installation was made of an oil-filled pipe-type power cable. This cable differed from the self-contained oil-filled cable in that three individually shielded cable conductors were placed in an oil-filled pressurized tube as delineated in Fig. 1.5; the conductor and insulation geometry were similar to the high viscosity oil-impregnated paper-type cable, whereas the overall insulation thickness was roughly the same as that of the oil-filled cable of equivalent voltage rating. Also, the viscosity of the oil under pressure within the pipe was appreciably lower than that of the oil impregnant in the oil impregnated paper insulation of the cables themselves. The higher viscosity oil impregnant was required to prevent loss of impregnant from the paper insulation during the pulling procedure of the cables into the pipe. The first pipe-type cable, manufactured by the Okenite Company, was placed in an 8 in. diameter steel pipe with the insulation thickness of each of three-phase conductors, having an average value of 0.375 in. [9]. The experimental length was found to perform very well, and the first commercial installation of the pipe-type or Benett cable as it was initially called (after its inventor), took place in 1935. A total length of 17,000 ft of pipe-type cable rated at 132 kV was installed in Baltimore; an insulation thickness of 0.675 in. was used with the oil pressure set at 200 $lb/in.^2$ and the operating temperature at 70°C. The pipe-type power cable proved to be more competitive economically, and by about 1954 the total circuit mileage of installed pipe-type power cable in the United States surpassed that of the self-contained oil-filled cable (cf. Fig. 1.6).

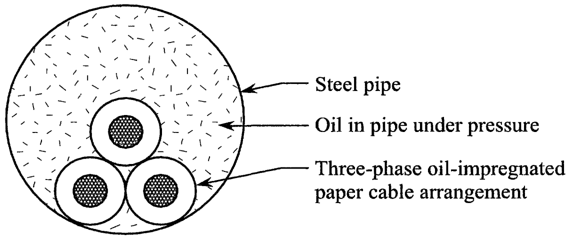


Figure 1.5 Oil-filled pipe-type power cable with three individually shielded oil-impregnated paper cables.

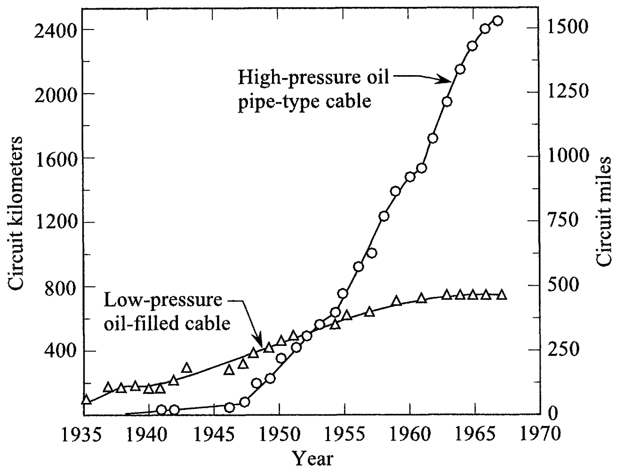


Figure 1.6 Early underground oil-type power transmission cable use in the United States in the voltage range from 69 to 345 kV (according to [10]).

The corrosion-resistant steel pipe enclosing the individual conductors of the pipe-type cable provides excellent mechanical protection to the three-phase system. It has been found to be particularly well adapted for servicing congested areas where usually the saving achieved in space is very significant as compared to self-contained oil-filled cables. Although pipe-type cables have been mainly used for underground installations, they can be installed as suspended systems in air or for submarine runs. However, in the latter case the corrosion-protective coating on the pipe must be supplemented by cathodic protection. Another marked advantage of pipe-type power cables lies with the fact that they normally are three-phase systems and thus have no problems associated with metallic sheath voltage rises or sheath losses as in the case of single- conductor metallic sheath cables. The working pressures of pipe-type cables vary from 150 to 220 lb/in.^{2} and are thus substantially higher than those of hollow-core cables. The reason for this lies in the fact that the latter use a much lower viscosity oil (approximately 10 cP at room temperature). Since in pipe-type cables the occurrence of partial discharge is prevented by maintaining a sufficiently high pressure on any gas inclusions within the insulating system, the term high-pressure pipe-type cable is often used. As the individual conductors are not covered with a lead sheath, the relatively light weight of pipe-type cables allows pulling lengths up to 3500 ft during the installation process. To provide increased mechanical protection and to facilitate sliding movement, the individual cables are now constructed with a skid wire that runs spirally over the outside shield, thus minimizing the contact area between the inner surface of the pipe and the outside surface of the individual cable phases. The portion of the skid wire that is contiguous with the cable shield is flat. The skid wire arrangement represents an appreciable amelioration over the antecedent canvas wrapping used in the Benett cable [9]. Much the same as for the oil-filled cables, the operating voltages of pipe-type cables have been continuously on the increase over the first few decades following their introduction. The first 230-kV pipe-type cables in the U.S. were installed in 1956 at Garrison Dam, North Dakota. In 1964, the first 345-kV pipe-type cable was installed in New York City; its load rating was set at 484 MVA as compared to 188 MVA for an equivalent 138-kV cable [10].

The load-carrying capacities of cables of existing oil-paper designs may be further augmented by the use of forced cooling so as to remove the heat generated in both oil-filled and pipe-type cables. In pipe-type cables this is most easily accomplished by circulating and cooling the pipe filling oil, whereby the losses are usually reduced by about 50%. Circulation of the oil only already gives the decided advantage of maintaining a uniform temperature throughout the cable, thereby reducing the possibility of hot-spot zone instabilities. In present practice, forced cooling of self-contained oil-filled cables is most economically carried out by placing metal water-circulating tubes adjacent to the cables depicted schematically in Fig. 1.7. Other simple techniques of forced cooling involve submersion of cables in water troughs or enclosure of individual cables in cooled water pipes. A more sophisticated method of cooling being experimented with recently involves the heat pipe principle. Presently contemplated forced-cooling techniques could conceivably extend the capacity of dielectric liquid or oil-impregnated cables above 2000 MVA. However, for much greater loads neither increased cooling nor operating voltage (above 750 kV) can efficiently cope with the enhanced dielectric losses in the oil-impregnated papers themselves. Thus, for operating voltages in the range from 750 to 1000 kV, the oil-impregnated-paper dielectric must necessarily be replaced by low dielectric loss synthetic papers. In the 1980s composite paper-polypropylene-paper tapes, possessing inherently lower dielectric losses, became commercially available, and oil-pressurized cables with these types of composite tapes were produced. In Fig. 1.8 is portrayed a cross section of an 800-kV self-contained branched dodecyl-benzene dielectric liquid cable constructed with these tapes [11].

The composite polypropylene-paper tapes consist of a polypropylene film sandwiched between two kraft paper tapes. The dielectric loss and dielectric constant of this combination may be reduced by increasing in proportion the thickness of the polypropylene tape with respect to that of the two kraft paper tapes. For example, increasing the polypropylene-to-paper ratio from 42 to 60% reduces the dielectric constant and dissipation factor from 2.8 and 1×10^{-3} to 2.7 and 0.7×10^{-3}, respectively [9]. Table 1.1 provides additional data on the characteristics of the composite polypropylene–kraft paper tapes, with a polypropylene-to-paper ratio of 60%. Figure 1.9 illustrates the reduction in the overall losses of an 800-kV branched dodecyl-benzene-impregnated cable insulated with composite paper-polypropylene-paper (PPP) tapes as compared to equivalent kraft paper tape insulated self-contained dodecyl benzene filled cables for operation at 800 and 500 kV. The 800-kV PPP–dodecyl-benzene-filled cable is seen to have losses substantially lower than the 800-kV kraft paper–

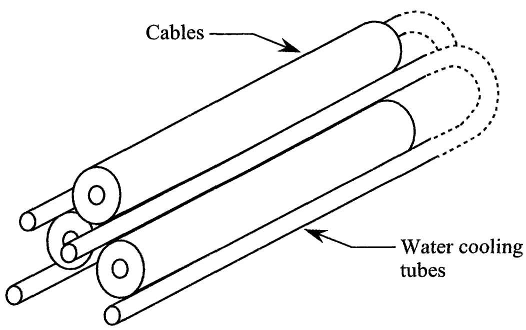


Figure 1.7 Forced-water-cooled cables [5].

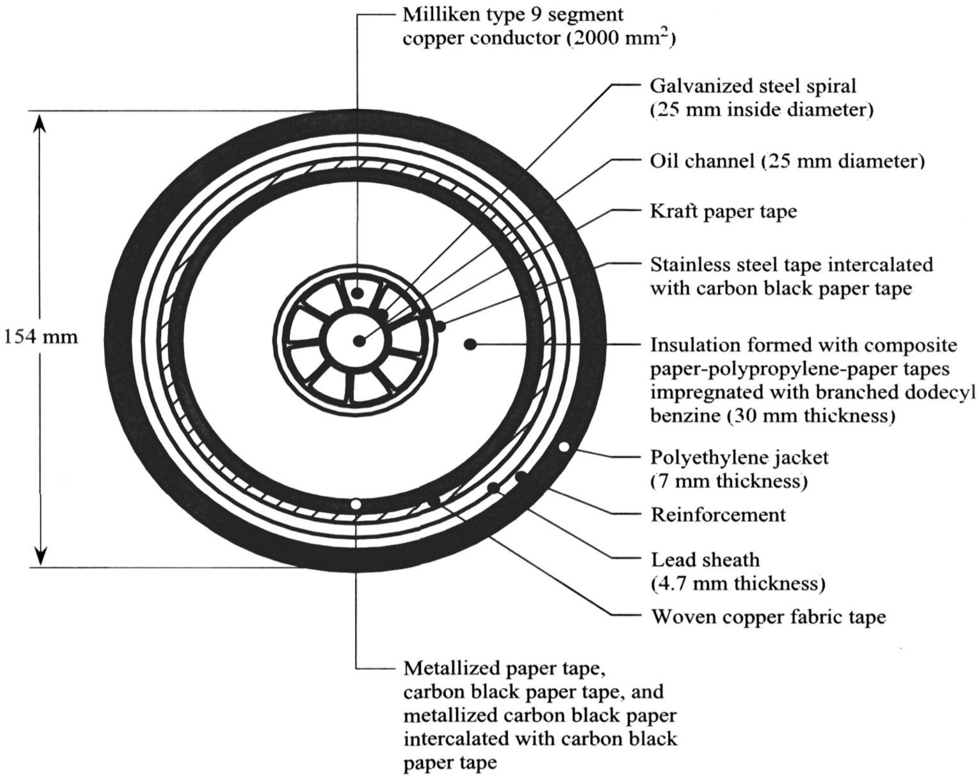


Figure 1.8 Cross section of 800-kV kraft paper–polypropylene–kraft paper (PPP) self-contained branched dodecyl-benzene–filled cable [11].

TABLE 1.1 Electrical Characteristics of Polypropylene–Kraft Paper Composite Tapes (PPP) and Kraft Paper Tapes Impregnated with Branched Dodecyl Benzene

	PPP Tape Thickness (μm)			Kraft Paper Tape Thickness (μm)
Electrical Parameter	120	170	220	200
Dielectric constant	2.57	2.58	2.61	3.4
Dissipation factor at 20 kV/mm, 80°C	5.4×10^{-4}	5.3×10^{-4}	5.9×10^{-4}	2.0×10^{-3}
ac breakdown strength, kV/mm	172	150	139	80
Impulse breakdown strength, kV/mm	284	256	245	150

Source: From [11].

dodecyl benzene filled cable and even slightly lower losses than a kraft paper–dodecyl-benzene-filled cable for operation at a reduced voltage of 500 kV. It is apparent from Fig. 1.9 that with the PPP self-contained dielectric liquid-filled cables one can readily obtain transmission capacities of the order of 2000 MVA even without a resort to forced cooling.

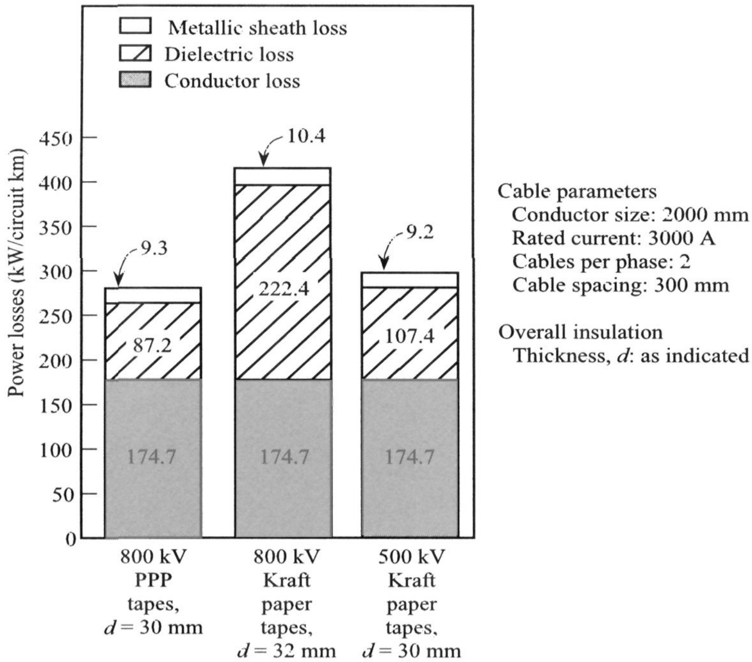


Figure 1.9 Comparison of power losses in 800-kV polypropylene–kraft paper self-contained branched dodecyl-benzene-filled cable and kraft paper self-contained branched-dodecyl benzene-filled cables (after [11]).

1.2.3 Solid-Dielectric-Extruded Power Transmission Cables

Following the introduction of solid-polyethylene-extruded power distribution cables in the 1950s, it became only a question of time until, with improved technology in materials and extrusion techniques, polyethylene would be applied to transmission cables. In these early days, polyethylene, because of its intrinsically low dielectric loss characteristics, was always viewed as an attractive substitute for the more traditional solid-liquid insulating systems. The last two decades have witnessed a marked increase in the number of solid-dielectric-extruded polyethylene transmission cable installations with increasingly higher operational voltages. Both from the environmental and maintenance considerations, the elimination of possible oil leaks and hydraulic oil reservoir tank systems have become attractive notwithstanding the current improvements in pressurized oil/dielectric liquid cable systems themselves. This tendency has continued to gain momentum in the face of the proven reliable long-term performance of the oil-paper cables with their termination and joint accessories. Presently, extruded cross-linked polyethylene (XLPE) cables are being designed for operation at 500 kV; joints and terminations of such cables form a very critical integral part of the overall cable system, and their design and continuing improvements are consuming much of the overall effort at this time.

Remarkable advances in the field of power transmission cables have been achieved initially by the French, who have made use of a thermoplastic-type low-density linear polyethylene (LDPE) on 225-kV cables. These cables have operated successfully since the time of their initial installation date in 1969, and by 1981 the total length of these cables used in the Électricité de France system had already reached 142 km [12–14]. The cables have been designed with a wall thickness of 22 mm to operate at a maximum voltage gradient of 100 kV/cm. The French cable design cross section is portrayed in Fig. 1.10. During the summer months, the cable depicted in Fig. 1.10, which has a copper (800 mm^2) conductor, is capable of carrying a load current of 750 A or a load of 290 MVA at a temperature of 70°C; the rated load-carrying capacity is approximately the same as that for an equivalent kraft paper self-contained oil-filled cable or slightly more as that of an oil-filled pipe-type cable. In 1985, the voltage of the subsequently manufactured LDPE cables was extended to 400 kV, corresponding to maximum operating stresses between 120 and 150 kV/cm. Finally, in 1995, LDPE cables were introduced for operation at 500 kV. Table 1.2 summarizes the French experience with LDPE power transmission cables [15]. Similar development work was undertaken in Germany in 1980 with projected cable insulation thicknesses between 25 and 28 mm [13, 16] where use was already being made of solid extruded dielectric cables for transmission voltages up to 100 kV.

The introduction of thermosetting-type solid extruded XLPE as the cable insulant on transmission cables resulted in an increase of 20°C in the operating temperature above that of 70°C allowable for the thermoplastic LDPE-insulated cables. The early work on XLPE insulation for power transmission cables has primarily been centered in Norway, Japan, Sweden, and the United States [13]. A lead-sheathed XLPE cable rated for 138 kV was commissioned for operation in 1976 at the Detroit Edison Company. The cable itself appears to have performed well initially, though difficulties were encountered with the joints. Subsequently, again in the United States, many studies have been carried out over the past several decades to perfect the 138-kV rated XLPE cables with efforts being directed toward improving cleanliness of the insulation and semiconducting shield interfaces, obtaining a more uniform distribution of the cross-linking agent, reducing cavity formation by increasing the extrusion pressure, and replacing the wet curing with a dry-curing process. This resulted in the production of 230-kV cables and the design of a 345-kV cable in 1980 [17]. In Norway four conductor lengths of 420 m of a 300-kV cable insulated with XLPE have been installed in 1980, and in Sweden 75 km of a 170-kV XLPE cable were put in service by the end of the same year [13, 18]. In Japan, it is now an established practice to employ XLPE-insulated power transmission cables at 275 kV along mountain slopes on power station reservoir sites [19, 20]. Work in Japan has progressed rapidly toward the development of 500-kV XLPE power transmission cables [21] with the first experimental length being actually placed in service in 1990 [22]. Similar work has been underway in France [15],

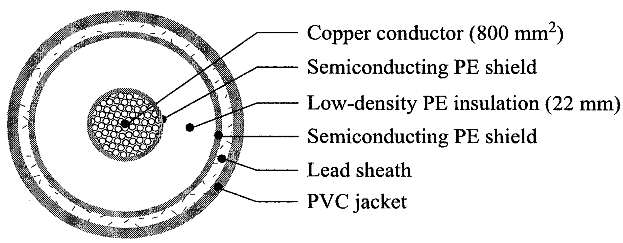


Figure 1.10 Cross section of 225-kV low-density PE power transmission cable [12].

TABLE 1.2 In-Service Experience with LDPE Power Transmission Cables in France (up to 1995)

Voltage (kV)	Total Length of Cables (km)	Number of Terminations	Number of Joints	Date of First Installation
225	1195	3223	2055	1969
400	40	176	22	1965
500	< 1	2	1	1990

Source: From [15].

England and Italy [23], and Germany [24]. Figure 1.11 depicts a typical cross section of an extra-high-voltage XLPE cable. Stresses in these cables usually range between 7 and 14 kV/mm, though maximum stresses as high as 27 kV/mm are contemplated. With the number of experimental and in-service installations of solid extruded dielectric transmission cables on the increase, meaningful data should begin finally to accumulate. It will be of great interest and practical significance to see whether extra-high-voltage polymeric transmission cables can achieve the same proven long-term performance reliability that has been so characteristic of oil-filled-type power transmission cables. The possibility of cavity occurrence and the propensity to electrical or water tree growth in polyethylene pose some uncertainties in this respect. On the other hand the low value of the dielectric constant and dielectric loss is an intrinsic property of plastic insulation that provides an ideal low-loss medium for underground alternating-current (ac) power transmission over relatively longer distances because of the lower associated capacitive charging currents. Moreover, plastic insulation is also attractive from the safety perspective because it does obviate the use of dielectric liquid or oil reservoirs and any possible oil leak difficulties that do arise occasionally with oil-filled cables.

In view of the relatively short experience, both in operational time as well as total cable length in operation, it is difficult to arrive at this time at a long-term prognosis on the expected performance of present and future 500-kV linear polyethylene and XLPE-insulated power transmission cables. A reliable long-term performance assessment would necessarily require answers to a number of pertinent

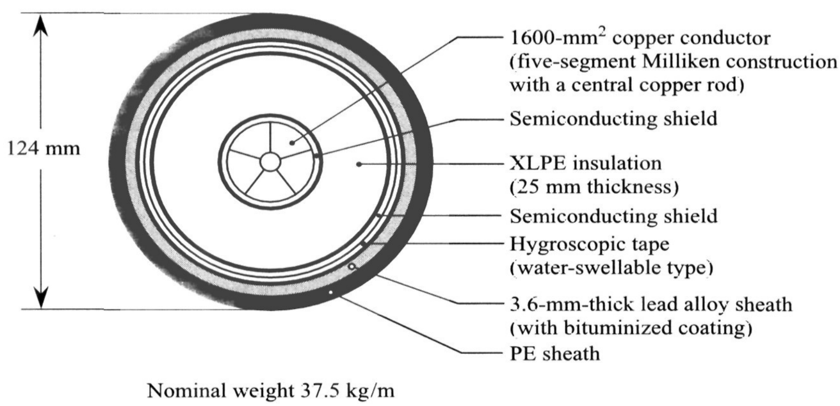


Figure 1.11 Cross section of 420-kV XLPE power transmission cable [22].

questions concerning the long-term thermal behavior of these cables [25]. For example, since crystalline regions in XLPE melt over a relatively wide range [26], the influence of oxidation on the partially crystalline polymer will differ substantially at the operating temperature (90°C) from that at the emergency temperature (130°C). Much of the needed oxygen for the oxidation of the polymer can be provided from the air entrapped at the corrugated metallic jackets of the cable as well as from the air dissolved in the solid components of the cable. The oxidation process will be retarded to some extent initially by a diffusion of the remnant antioxidants from the amorphous regions of the polymeric insulation [27] as well as from the semiconducting shields [28]. At elevated temperatures in addition to the more pronounced oxidation rates, the solubility of residual crosslinking agent by-products (acetophenone, cumyl alcohol, and dimethyl styrene) will be enhanced; although it is not known what influence this effect may pose to the long-term stability of the XLPE insulation in the extra-high-voltage cables. However, the very marked depression of the mechanical modulus at the emergency temperature of 130°C may result in thermomechanical damage in the cables. To circumvent this possibility, the emergency temperature would have to be reduced to the temperature of the polymer melting point of ca. 105°C or lower. Moreover, temperature changes, due to load cycling of the cable, may cause cavity formation arising from melting and subsequent recrystallization effects [29]. However, the diameter of these cavities may be too small to sustain partial discharge, unless coalescence of some of these cavities takes place. Other detrimental effects may arise with the in situ molding of splice joints that require temperatures as high as 150°C, which may lead to water formation from the decomposition of cumyl alcohol (a product of dicumyl peroxide) [30]. Subsequent water condensation may induce microcavity formation, thereby resulting in water tree growth that could conceivably lead to eventual failure of the high-voltage cable splice.

1.2.4 Solid Extruded Dielectric Power Distribution Cables

In terms of mileage, the amount of installed and manufactured volume of power distribution cables exceeds many times that of power transmission cables. Prior to and within the early 1950s various forms of rubber had been utilized in distribution-voltage cable-insulation applications, where flexibility and ease of handling were required as compared to the usually much more rigid solid-type high-viscosity oil-impregnated PILC cable systems. Butyl rubber compounds, because of their desirable electrical properties, were the most commonly employed materials for extruded solid-dielectric insulating systems. Following the discovery of the hydrocarbon thermoplastic polyethylene (PE) in England in 1933, polyethylene became rapidly the insulant of choice for RF (radio frequency) coaxial cables. It took a substantially longer time for polyethylene insulation to be introduced into the power cable area. However, since the time of its general acceptance in the 1950s, power distribution cables insulated with polyethylene have replaced virtually all of the butyl rubber cables and a significant portion of the oil-impregnated-paper insulated power cables used at operating voltages up to 35 kV [31]. But lower voltage PILC cables are still being manufactured, and there are many utilities in North America and overseas where PILC cables, due to their in-service longevity and reliability, continue to constitute a very substantial part of the overall underground distribution network.

Initially, the plastic cables manufactured in North America were made using low-density high-molecular-weight polyethylene (HMWPE); the latter is a thermoplastic material and, consequently, undergoes softening and flow at elevated temperatures. Its melting point is 105°C. The maximum normal operating temperature for HMWPE has been set at 75°C, with an emergency rating fixed at 90°C. It has been used since 1951 for distribution voltages up to 35 kV and sometimes higher [32]. Commencing with 1964, a changeover began toward the deployment of crosslinked polyethylene, which is a thermosetting compound with a higher melting temperature and exhibits as well a slightly better resistance to partial discharges [33]. With XLPE distribution cables, the conductor operating temperature is increased to 90°C and the emergency rating to 130°C. This improvement infers an equivalent ampacity increase of 12% over an HMWPE insulated cable or, alternatively, a proportional reduction in the conductor size for the same ampacity [33].

The early thermoplastic PE distribution cables, as well as their antecedent rubber cable counterparts, used carbon black tape conductor and insulation shields as opposed to the present-day cables, which utilize extruded semiconducting PE shields that provide better bonding between the insulation and conductor shields, thereby reducing the possibility of cavity occurrences at these interfaces and, hence, the incidence of partial discharge. Also the extruded semiconducting material has the advantage of smoothing out any sharp edges or protrusions on the conductor surface, thereby reducing the possibility of electrical and water tree growth at such asperity-like nucleation sites. The relatively low dielectric loss magnitude in the various PE-type insulations renders them exceptionally attractive for high-voltage applications; however, they are very susceptible to partial discharges and tree growth. Due to occasional imperfections in the extrusion technique, cavities tend to form in the extruded PE insulation wherein partial discharges can occur at sufficiently high voltage stresses; if the partial discharges are sustained for any appreciable length of time, failure of the PE insulation of the cable system follows inevitably. Though the exact nature of water tree growth mechanism is not fully understood, it has been observed to occur primarily in cables operating in high-moisture environments and to be much more prevalent in the earlier cable designs using linear or branched HMWPE cables constructed with carbon black tape shields. The incidence of water treeing was substantially reduced by the replacement of the carbon tape shields with extruded thermoplastic semiconducting shields and by the addition of tree-retardant compounds to the low-density HMWPE and eventually by the elimination of the linear low density HMWPE itself by XLPE. Finally, the 1980s saw further remarkable advances made to control water treeing by the introduction of the dry-curing process, supersmooth and clean semiconducting shields, and ultra clean, tree-retardant XLPE (TRXLPE).

In the late 1960s, ethylene-propylene-rubber (EPR) insulated cables, having clay filler contents as high as 50%, appeared on the market for voltage ratings up to 60 kV. These cables have a better flexibility than crosslinked PE, although they, very much like the thermoplastic PE and thermosetting XLPE cables, are still susceptible to partial discharges and tree growth. They are generally preferred over XLPE where mechanical flexibility is of prime concern. The operating and emergency temperature limits of EPR cables are identical to those of XLPE cables. Also the permissible short-circuit current value for both EPR and XLPE is set at 250°C as opposed to 150°C for HMWPE. The dielectric losses in EPR cables are much higher than those in either XLPE or HMWPE; these losses contribute to a significant energy loss at the higher operating voltages with the result that the use of EPR above 69 kV is less desirable unless for some reason cable flexibility is of paramount importance. It is noteworthy that it is only in North and South America and Italy that EPR cables are used to any great extent. In Italy already by the end of 1980, a total of 9000 km of EPR cable had been installed of which about 100 km were designed for 66-kV operation [13]. In North America in the distribution power cable area within the range from 5 to 35 kV, most utilities have now standardized on the use of thermosetting (XLPE or EPR) insulated cables. In this construction, the extruded shield over the conductor is most often semiconducting XLPE, though in some cases semiconducting EPR may be used. Over the insulation, the extruded shield is generally composed of semiconducting LDPE or XLPE. The jacketing materials normally employed consist of neoprene over EPR insulated cables and PVC or linear low-density polyethylene (LLDPE) over XLPE insulated cables. A TRXLPE cable construction, typical of the current practice followed in the 1990s, is depicted in Fig. 1.12; in parentheses are shown the common compounds employed earlier.

The cable portrayed schematically in Fig. 1.12 is of a concentric neutral construction in which the neutral is formed by a metallic tape shield. However, the shield may consist also of alternative constructions as, for example, a flat copper strap concentric neutral, a round copper wire concentric neutral, a small copper wire shield, or a corrugated metallic tape shield [32]. With strap and round copper wire concentric neutrals, it was a common earlier North American design practice to omit the jacket over the cable. In European primary distribution cable practice, it is normal to enclose the cable within a metallic sheath; although this adds considerable cost to the cable, it does provide protection against water ingress and water tree formation. The North American approach is to use metallic sheaths only on polymeric cables that are for special applications or that are to be used as transmission cables at EHV. It should be noted that with secondary distribution cables, i.e., those operating at 600 V or less, the neutral may consist of a separate single insulated conductor as in the triplexed construction or it may be applied in the form of coated solid copper wires around the two insulated conductors as in the parallel or two-phase arrangement [32]. As with all polymeric cables, either aluminum or copper conductors may be used. With larger conductor sizes in order to retain the necessary flexibility, the conductor must be stranded; while with smaller sized cables, the conductors may be either solid or stranded.

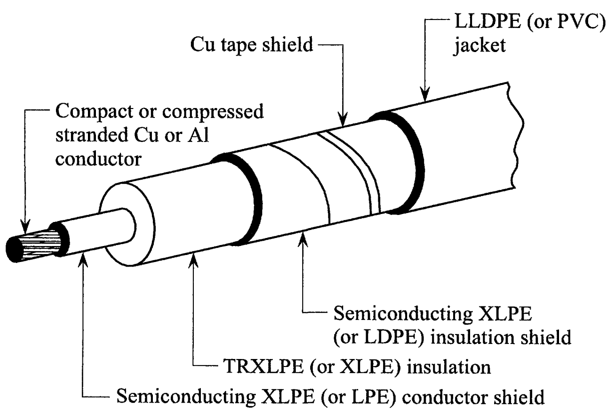


Figure 1.12 Typical TRXLPE (or XLPE) insulated power distribution cable.

There has always been considerable interest in the reliability of plastic insulated power distribution cables vis-à-vis the old conventional solid-type high-viscosity oil-impregnated PILC power cables. In the past, a great deal of statistical data on plastic insulated cables has been accumulated in the United States [17]. In this regard two rather revealing curves (released in 1978) are presented in Figs. 1.13 and 1.14, where failure rates are shown as a function of the year of installation for distribution cables rated between 5 and 36 kV. It can be discerned that whereas the failure rates up to 1978 of both HMWPE and XLPE were still on the increase with the year of installation, the failure rate of PILC cables, though higher, had reached a near asymptotic value. In examining the data further, one can also deduce the prognosis made by Thue et al. [17] that to attain a 10-fold cumulative failure rate, 6.2 years are required for HMWPE cables as opposed to 7.5 years for the XLPE cables. On the other hand for PILC cables, this value is reached in 100 years; although in the early years of PILC cable operation, the 10-fold increase had been manifest within 25 years (between the years 1925 and 1937). However, it was astutely predicted in 1980 by Eichhorn [34, 35] that as better materials appear and improved cable extrusion processes are developed, the performance of the plastic insulated cables should also improve just as it was the case with the early PILC cables. These predictions have indeed been borne out by the substantially improved performances of the XLPE and TRXLPE insulated distribution cables installed in the 1980s and 1990s. Furthermore, Eichhorn demonstrated that by analyzing statistically the results in [17] and comparing the situation where the total installed cable length of XLPE cables equals that of the PILC cables, the performance of XLPE in fact would appear better than that of PILC cables. Evidently, considerably more service data is necessary before definite trends in the failure rates and their full ramifications can be fully ascertained as concerns the comparative long-term performance of HMWPE, XLPE, and PILC distribution cables. For example, the type of soil for direct buried cables is an important parameter. Cables in wet soils may have to be rated higher than those in dry soils; but some discretion is required here since the soil conditions may vary appreciably with the seasons of the year.

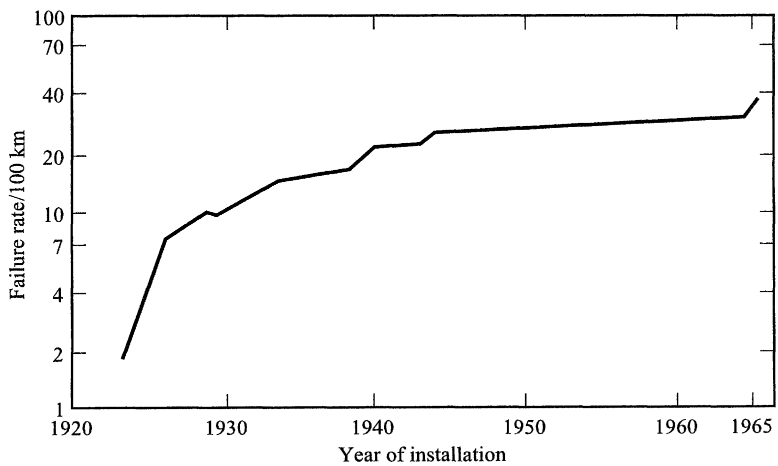


Figure 1.13 Cumulative rate of electrical failures of early PILC power distribution cables in the United States [17].

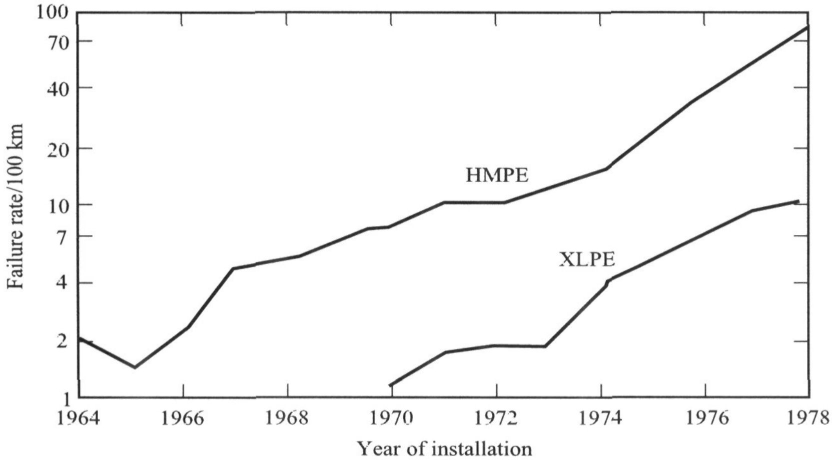


Figure 1.14 Cumulative rate of electrical failure of early HMPE and XLPE power distribution cables in the United States [17].

A rather revealing study on polymeric distribution cable failures was carried out by an Association of Edison Illuminating Companies (AEIC) Cable Engineering Section Task Group that collected HMWPE and XLPE distribution cable failure data between 1989 and 1991 [36]. The investigation examined the influence of electrical stress or cable insulation thickness and the type of cable jacket upon the in-service life of low density HMWPE and XLPE insulated distribution cables installed in ducts and directly buried. The findings are delineated schematically in Fig. 1.15 from which it is readily perceived that jacketed XLPE-insulated cables installed in ducts exhibit a low failure rate in contrast to the relatively high failure rates characterizing the directly buried unjacketed low-density HMWPE cables. Increased electrical stress or reduced cable insulation wall thickness is seen to affect adversely the failure rate of both the HMWPE and XLPE

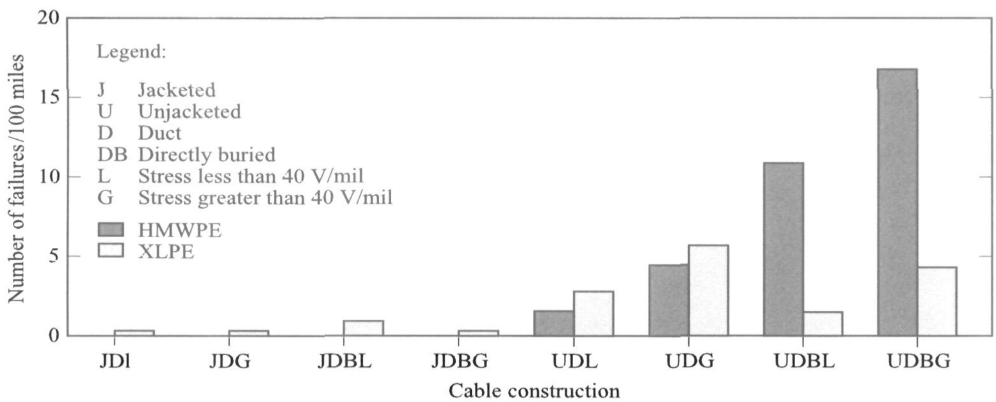


Figure 1.15 Low-density HMWPE and XLPE insulated power distribution cable failures in United States recorded between 1989 and 1991 (AEIC Cable Engineering Section Task Group [36]).

cables. Surprisingly, the unjacketed HMWPE insulated cables outperform the unjacketed XLPE insulated cables, when both are installed in ducts.

The intricate aging behavior and subsequent failure of solid extruded dielectric power distribution cables, under operating conditions in the field, are currently continuing to attract much attention. Considerable efforts have been expended toward developing suitable nondestructive diagnostic test procedures to determine a quantitative measure of the degree of aging of these cables while in service. One of the most popular diagnostic techniques in use currently is that of low-frequency testing, particularly as concerns the measurement of partial discharge and the dissipation factor [37–39]. Convenient lightweight low-frequency (0.1 Hz) high-voltage sources, having low kilo-volt-ampere ratings in comparison to equivalent high-voltage 60-Hz sources, have become commercially available, thus permitting partial-discharge site location as well as dissipation factor ($\tan\delta$) measurements to be made on distribution cables in the field. Since space charge effects predominate at low frequencies, particularly in aged cables, great care must be exercised when interpreting the $\tan\delta$ measurement; in the presence of space charge effects, the $\tan\delta$ value obtained at 0.1 Hz will generally exceed that at 60 Hz by an appreciable amount [40, 41].

A schematic circuit diagram of a typical 0.1-Hz test set is depicted in Fig. 1.16. The high-voltage dc is converted to a high voltage having a frequency of 0.1 Hz: A rotating rectifier in conjunction with a high-voltage choke convert the dc signal into an alternating polarity ac signal. The maximum 0.1-Hz alternating voltage output of the very low frequency (VLF) test set is typically 36 kV root mean square (rms) into a maximum capacitive load of 3 μF [42]. Low-frequency voltage withstand tests are also employed to assess aging of polymeric cables while in service [39]. They are frequently employed in lieu of the high-voltage dc tests, which are believed under some conditions to cause damage to aged polymeric cable insulating systems that may still have some useful life remaining under normal operating ac voltage conditions.

1.2.5 Underwater or Submarine Cables

Underwater or submarine cables, as their name implies, are used for traversing water bodies to interconnect systems, such as those between an island and an adjacent shore line. Submarine cables may generally be of the self-contained oil-filled type, pipe type, high-viscosity oil-impregnated paper, or solid extruded dielectric type. For short-distance transmission for large quantities of power, ac self-contained oil-filled cables are

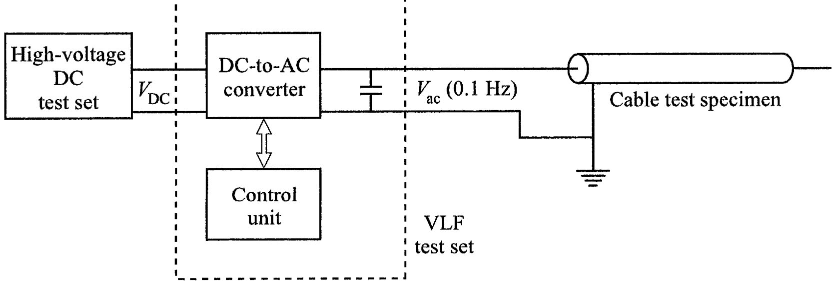


Figure 1.16 Very low frequency (VLF) high-voltage test set schematic with cable specimen under test (after [42]).

preferred. These cables make use of very low viscosity impregnating oils, which permit lower hollow conductor core diameters, guarantee positive oil feed to cable insulation under all load conditions, and prevent water ingress in case of external damage or failure. For power transmission over long distances low-cost solid-type high-viscosity oil-impregnated paper dc cables are deployed. Another application of dc cables concerns transmission system stability requirements, where isolation between two power networks must be provided; in the latter case, the distances may be short and the isolating dc intertie may involve either an underwater or a terrestrial crossing. For such short-distance dc cable applications, the self-contained oil-filled cable design is again the preferred choice. Submarine cables may traverse rugged land–water terrains and must, therefore, be well protected by steel wire armoring. Figure 1.17 depicts a profile of an ac submarine cable crossing at Long Island Sound [43] in which an oil-filled cable system, involving seven single-phase cables rated at 138 kV to supply a load of 300 MVA, was placed in service in 1970; the operating oil pressure in these cables is maintained between 179 (1170) and 270 lb/in.^{2} (1860 kN/m^2).

Perhaps one of the longest ac submarine cables installed was that in 1956 involving three single 138-kV gas pressure oil-preimpregnated-paper-type cables over a length of 80 miles across the Georgia Strait between Vancouver Island and the British Columbian mainland [5]. The cable system was designed to transmit a load of 100 MW. This transmitted load capacity exceeded substantially that of several important and almost concurrent earlier installations, namely the St. Lawrence River crossing in Québec in 1954 with a 75-kVA rated 69-kV ac single core oil-paper cable over a distance of 51 km; the Sweden–Gotland Island 100-kV dc oil-impregnated-paper cable over a distance of 100 km in the Baltic Sea for a load of 20 kVA in 1953; and, in 1951, the Sweden–Denmark 120-kV ac, flat three-core oil-filled cable rated for a transmitted load of 65 kVA over a distance of 5.5 km [44]. All of the foregoing power transmission capacities were again surpassed by that of the dc submarine cable link between England and France commissioned in 1961 [45]. The oil-impregnated-paper cables spanned a total distance of 52 km across the English Channel and were rated to deliver a maximum power of 160 MW at an operating voltage of ±100 kV dc. Over the last four decades the power transmission capacity of submarine cables has increased markedly with each rise in the ac or dc transmission voltage of the cables [46]. For example, the capacity of the ±450-kV dc submarine cable intertie across the St. Lawrence River between Québec and the New England states, commissioned in 1992, is 2000 MW [47]. The strong

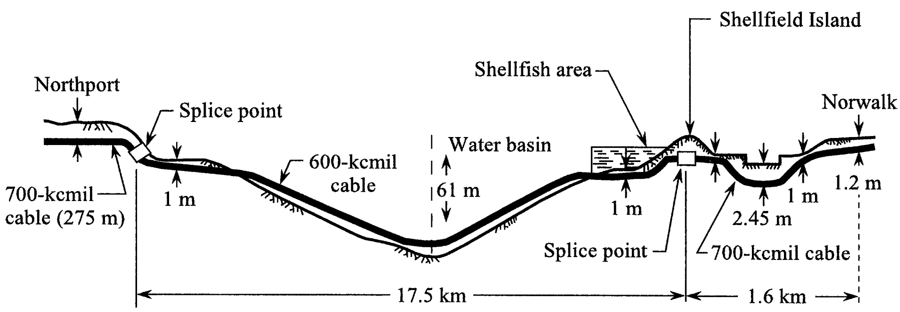


Figure 1.17 Profile of 138-kV oil-filled power cable crossing at the Long Island Sound (after [43]).

current, ship traffic, and patterns of ice flow in the river did not provide a benign environment to permit direct burial of the cables. A decision was thus made to install the cables in a 4.1 km long tunnel constructed in the limestone and shale strata beneath the riverbed. The tunnel has a 20-cm-thick circular shell of non-reinforced concrete as shown in Fig. 1.18, with the six 500-kV dc nominally rated self-contained oil-filled kraft paper tape cables placed on prefabricated reinforced-concrete troughs; a pair of cables act as spares, while four cables carry the load. Stability requirements dictated the deployment of dc cables in order to isolate the Québec system from the New England states systems. As mentioned already apart from system isolation applications, dc submarine cables are extensively used for longer underwater transmission distances where ac cables become uneconomical as a result of the excessive reactive power losses. For intermediate distances self-contained low-viscosity-type dielectric liquid-filled dc cables are preferred as higher voltages may be employed to transmit larger blocks of power. When the underwater distances become too large, at which time the required dielectric liquid pressures become too difficult to maintain, solid-type dielectric-liquid paper-impregnated dc cables must be employed with an attending compromise in the amount of transmitted power.

An interesting submarine cable design has been used in the crossing between New Brunswick and Prince Edward Island across the Northumberland Strait. Rated at 138 kV, two three-phase cables of the construction portrayed in Fig. 1.19 were laid to span a length of 13.5 miles. The cable construction is unique in the sense that it is basically a flexible oil-filled pipe-type cable. The rigid steel pipe of a normal pipe-type cable is replaced by a flexible lead sheath and armor, to provide a compact self-contained, pipe-type cable. Each cable is capable of carrying a 100-MW load under the present ac operating conditions; for optional dc operation with a ground return,

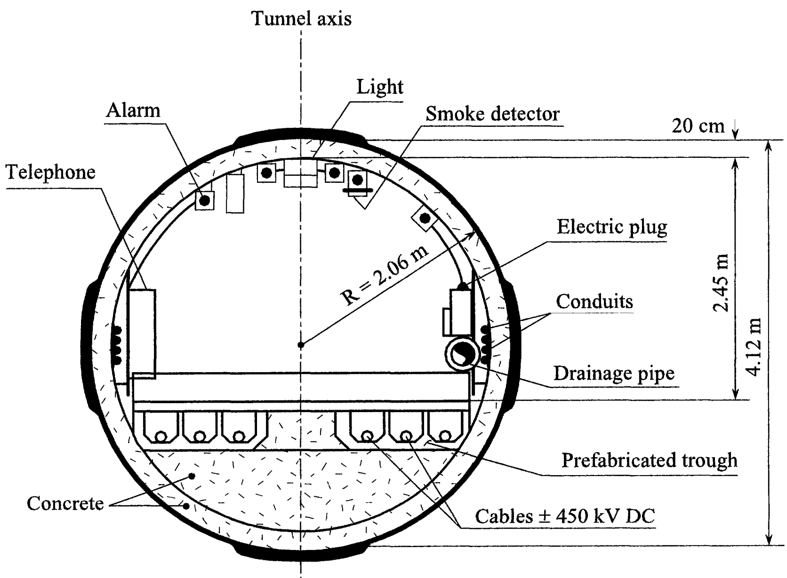


Figure 1.18 Disposition of six 500-kV dc nominally rated self-contained oil-filled cables in a submarine tunnel under the St. Lawrence River [47].

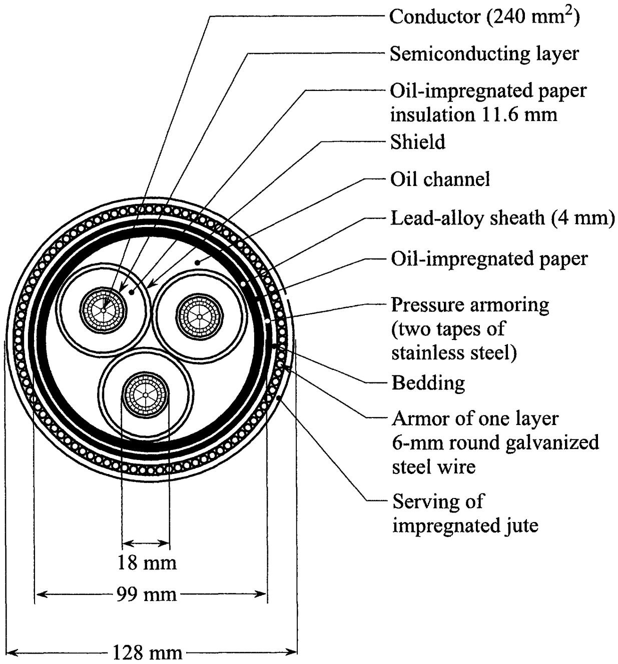


Figure 1.19 Cross section of Sieverts submarine power cable used on the Prince Edward Island–New Brunswick link. (Courtesy of the Maritime Electric Company.)

the capacity may be augmented to 300 MW per cable. For water depths in excess of 40 ft along the igneous crossing, the cables were plowed 2.5 ft below the ocean floor; whereas for depths less than 40 ft, specially dredged trenches were made for cable lays 6 ft below the ocean floor. Notwithstanding these burial precautions, the cable was damaged recently by a boat's anchor and had to undergo repairs with attending power interruptions on the island, which was fortunately equipped with standby thermal generator units.

Submarine cables have always been designed to withstand considerable mechanical stress and pressure, thus their construction is more robust than that of a normal type of underground cable. This is well borne out in the instance where a 72-kV oil-filled cable laid in Norway at a depth of 535 m in 1953 was subjected to excessive tensile stress during a storm at sea, resulting in appreciable radial deformation. The cable was nevertheless put in service and has remained in operation and as last reported on in 1980, without any interruption [48]. Though most submarine cables for operation under ac conditions are of the oil-filled or solid-type high viscosity oil-impregnated-paper design, an increasing number of XLPE-insulated cables are being installed. In Norway, a country that makes extensive use of submarine cables because of the geographical terrain of large numbers of fjords and islands, the first XLPE cable, rated at 12 kV, was installed in 1971. A total of 17 cables rated at 72 kV were already in operation in 1979 and a 145-kV rated cable was laid in 1980 [48]. The situation is rather interesting in the sense that the polyethylene cables placed for ac operation at or less than 24 kV are without a lead sheath; even some of the 72-kV cables have, in fact, been installed without an impervious lead sheath. In what manner this will affect water tree growth in the unsheathed submarine cables is not known, though it can be said that insofar as the reliability of performance of the lower voltage rated XLPE cables is concerned, no premature failures have yet been recorded. However, caution is to be exercised and the decision [48] in Norway in 1980 to apply lead sheaths on all future cables rated above 24 kV is certainly a very prudent one. At this juncture in our discussion, the appropriate question may be posed as to why terrestrial polyethylene power cables without hermetic sheaths when directly buried in moist soil are subject to tree growth and failure while submarine cables submerged in fresh or salt water are not. The only plausible explanation of the peculiarly divergent behavior of polyethylene cables in the submarine and terrestrial environments is the distinct possibility that the treeing mechanism thrives principally when the cables are being subjected to alternatively dry and wet conditions in the soil as is indeed the case with many terrestrial cables when water levels change during and with the seasons.

The application of XLPE insulation on dc submarine cables has met with considerable adversity; the excellent low dielectric loss characteristics of polyethelene result directly from its deep charge traps wherein free charge carriers are trapped and immobilized. But it is precisely these deep charge traps that render polyethylene unsuitable for dc power transmission. Polarity reversal under dc operating conditions can readily precipitate breakdown of the polyethylene due to the additive field of the space charge residing within the deep traps. It is well known that the incorporation of conductivity additives in the polyethylene can disperse some of the space charges, but the long-term effectiveness of these compounds is unknown. The long proven reliability of oil-paper systems for dc power transmission is difficult to improve upon. If it is desired to replace the oil-paper system for dc applications with substitutes, then perhaps it is more expedient to accomplish this with PPP tape composites [49] than with XLPE containing additives [50, 51].

1.2.6 Low-Loss Power Transmission Cable Systems

As rising urban population densities demand increasingly larger blocks of underground transmitted power, the present insulating systems of high-voltage power transmission cables are becoming subjected to more stringent performance requirements. With traditional dielectric liquid-impregnated kraft paper and solid extruded dielectric insulated cables, the rise in the demand of electrical energy can partially be met by raising the transmission voltage and adjusting accordingly the insulation wall thickness, and if necessary using forced cooling. However, even with adequate forced cooling techniques, the use of oil-impregnated kraft paper power cables cannot be efficiently extended much beyond 750 kV. Furthermore, even below 750 kV, when indirect forced cooling is employed, the required current ratings necessarily limit the lengths of the oil-impregnated kraft paper cables to a few thousand feet. It was demonstrated already in 1980 that higher load-carrying capacities could be achieved by direct cooling methods, such as placing the oil-filled cables in a water-filled cooling pipe [13]. This could conceivably result in cables being capable of carrying loads approaching those carried by overhead transmission lines. However, practical problems would arise as such procedures would require large quantities of water to be drained off whenever repairs were necessary. As discussed in Section 1.2.2, at voltages in excess of 750 kV, the dielectric losses may be maintained within an acceptable level by substituting the kraft paper with other synthetic polymeric materials such as PPP composites, having low dielectric loss characteristics. These systems when operated from 750 to 1000 kV can provide load ratings substantially in excess of 1000 MVA even without the aid of forced cooling.

The chemical and physical compatibility of polypropylene with mineral oils, polybutenes, and silicones was examined by Allam and his co-workers in a research project supported by the U.S. Department of Energy and the Electric Power Research Institute (EPRI) [52]. Various designs have been considered, and it was found that of the three evaluated dielectric liquids, polybutene appears to be most compatible chemically with the PPP composite material. Some swelling problems have been encountered with the polypropylene plastic, which, in addition, could not be fully impregnated to eliminate all of the minute cavities within its interstices. Moreover, cable bending problems were anticipated due to the inclusion of the polypropylene in a composite tape. In England work on the same laminate was also carried out by Arkell et al. [53] and prototype cables for operation at 132–275 kV were tested in 1980. The relative permittivity of these cables ranged from 2.6 to 2.8 as compared to 3.5 of the oil-impregnated kraft paper insulation, thus in effect reducing the capacitative charging current significantly in the synthetic insulation cables. In Section 1.2.2, an 800-kV PPP composite tape cable was described in which a dodecyl benzene impregnant was employed and for which no chemical compatibility problems were observed. The transmission capacity of the cable with natural cooling only was in the order of 1900 MVA.

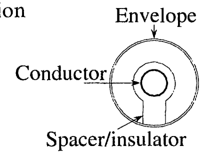
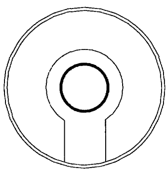
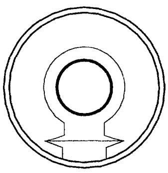
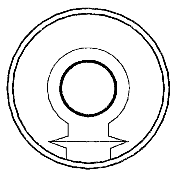
Both LDPE and XLPE have excellent low dielectric loss characteristics as well as low dielectric constants, which should place their power transmission capabilities well in excess of 1000 MVA. However, some questions remain concerning their long-term upper operating temperature limits. Further marked reduction in the dielectric loss of power transmission cables necessitates the replacement of either the solid or solid-liquid dielectric insulant with a gas or vacuum medium. Vacuum and gases, with the proviso that the gases are utilized at stresses well below their ionization level, represent virtually perfect dielectrics of near-to-zero loss. Also the use of vacuum or gas insulants diminishes very significantly the magnitude of the capacitive charging current, since the real value of the relative permittivity or dielectric constant of these insulating media approaches unity if the effect of the solid insulator spacers is neglected. Although air fits the low dielectric loss category of requirement, there are other more suitable gas dielectrics, whose dielectric breakdown strength either at atmospheric pressure or above exceeds that of air by an appreciable margin [54]. A further reduction in cable losses may be achieved with gases at cryogenic temperatures at which both the dielectric losses as well as the resistive conductor losses are greatly decreased with the cable conductor operating in the superconducting mode.

1.2.6.1 Compressed SF_6 Gas Power Transmission Cables

Compressed SF_6 gas cables with epoxy support spacer insulation have been in use for more than two decades [55, 56]. In 1974, an early experimental high-power capacity compressed gas cable, rated at 550 kV for 3000-A load operation, was installed and tested by Cookson [57] at Westinghouse; these early feasibility test results proved to be very encouraging and stimulated much of the work toward the development of practical high-power transfer compressed SF_6 gas lines. As a result of their high transmission capacities, compressed SF_6 gas insulated cable systems have gained considerable popularity, particularly for short transmission distances where they can carry directly the power from an overhead line to a substation. For such short distances they present a lower cost as compared to conventional dielectric liquid or oil-filled cable systems with the associated terminal and auxiliary equipment [13]. Their use is also attractive for substations already having apparatus with compressed SF_6 gas insulation; in a number of ways, such cables may be regarded as extensions of existing compressed SF_6 gas bus systems.

A good example of the applicability of compressed SF_6 gas cables for connection between overhead lines and substations is the extensive use of these cables made in Japan. Commencing with 1979, the first compressed SF_6 line rated for 154 kV was installed; this was followed by a 275-kV line in 1980 and a 500-kV line in 1985. Table 1.3 tabulates the characteristic parameters of four compressed SF_6 gas cables installed between 1979 and 1990 [58]. It can be perceived from Table 1.3 that the transmitted power capacity of compressed SF_6 gas cables is substantially augmented with increasing transmission voltage. The increase in voltage rating is achieved by enlarging the spacing between the inner conductor and the outside tube enclosure of the line, i.e., the length of the epoxy insulator and its contour or geometric configuration. Increased current-carrying capacity requires inner conductors with greater outside diameters and support/spacer insulators with higher operating temperature limits. Hence, irrespective of whether increased power transfer is attained by an increase in the operating voltage or current, a larger outside cable diameter is the net result. Table 1.4 presents

TABLE 1.3 Characteristic Parameters of Compressed SF_6 Gas Power Transmission Lines

Commissioning Date	1979	1980	1985	Line 1, May 1988 Line 3, March 1998
Nominal voltage	154 kV	275 kV	500 kV	275 kV
Rated current	2000 A	4000A	6240A	8000A
Route length	Line 1, 164 m Line 2, 199 m	102 m	Line 1, 152 m Line 2, 140 m	Line 1, 153 m Line 2, 138 m
Cable cross section				
Outer diameter of conductor	100 mm	160 mm	180 mm	180 mm
Inner diameter of enclosure	340 m	480 m	480 m	480 m
Type of insulators	Disk, cone, and post	Disk, post, and cone	Post, cone (with a rib)	Post, cone (with a rib)
Gas pressure	0.35 MPa at 20°C	0.35 MPa at 20°C	0.6 MPa at 20°C	0.5 MPa at 20°C
Conductor temperature	90°C	90°C	90°C	105°C
Construction details				
Conductor jointing	Welding	Plug-in contact	Plug-in contact	Plug-in contact
Enclosure jointing	Sleeve joint, and flange joint by welding	Sleeve joint and flange joint by welding	Plug and socket joint by welding	Plug and socket joint by welding
Welding method of enclosure joint	Manual	Manual	Automated	Automated

Source: After [58].

TABLE 1.4 Parametric Data for a Typical 275-kV Compressed SF_6 Gas Power Transmission Line with a Current Capacity of 8000 A

Number of conductors per tube enclosure	1
Conductor	
Outer diameter	180 mm
Thickness of hollow conductor	20 mm
Material	Aluminum alloy
Treatment of surface	Black alumite
Enclosure	
Inner diameter	480 mm
Thickness of tube conductor	10 mm
Material	Aluminum alloy
Treatment of surface	
Inner	None
Outer	Epoxy coating
Spacer	
Material	Epoxy resin
Geometric configuration	Post and Cone
SF_6 gas	
Pressure	0.5 MPa at 20°C

Source: After [58].

more detailed data on the dimensions and materials utilized in a 275-kV compressed SF_6 gas cable designed for a current-carrying capacity of 8000 A [58]. For both the inner hollow conductor and the outside cable tube enclosure, aluminum alloys are employed. Epoxy resin insulators, having a post-and-cone configuration are used with an SF_6 gas pressure of 0.5 MPa maintained at 20°C.

Compressed gas cables differ from conventional solid and solid-liquid insulated cables in that they are supplied by the manufacturer in sections and must be assembled in the field to complete their installation. The complete line assemblage consists of straight pipe units, which generally contain branched or T-connection sections and hinged aluminum bellows to allow for thermal expansion and contraction of the tube enclosures, as well as elbow sections and air insulator terminals. The configuration of some of these sections is illustrated in Fig. 1.20. The bellows of the straight sections also contain hinged conductors. The straight sections consist of extruded aluminum pipes, which may be in lengths of 12 or 14 m that are welded together at the plug and socket joints. The conductors within the pipes are joined by means of plug-in contacts.

The assembly of compressed gas cables in the field is frequently a cause and source of contamination, which may be in the form of different types of dust such as sand (SiO_2) and metallic particles [59]. The greater the number of sections to be assembled i.e., the longer the length of the required compressed SF_6 gas cable, the higher is the probability of contaminant particle incidence. This tacit constraint imposes in effect a practical limit on the length of compressed gas cables that can be assembled in sections. Metallic particles, which may comprise particle remnants from the manufacturing process of the pipes, or which may be produced by friction arising between the surfaces of movable parts in the system or due to other mechanical effects, affect adversely the breakdown voltage of the gas cables [60]. As the metallic particles execute motion under the influence of the existing electrical field between the conductor of the cable and the

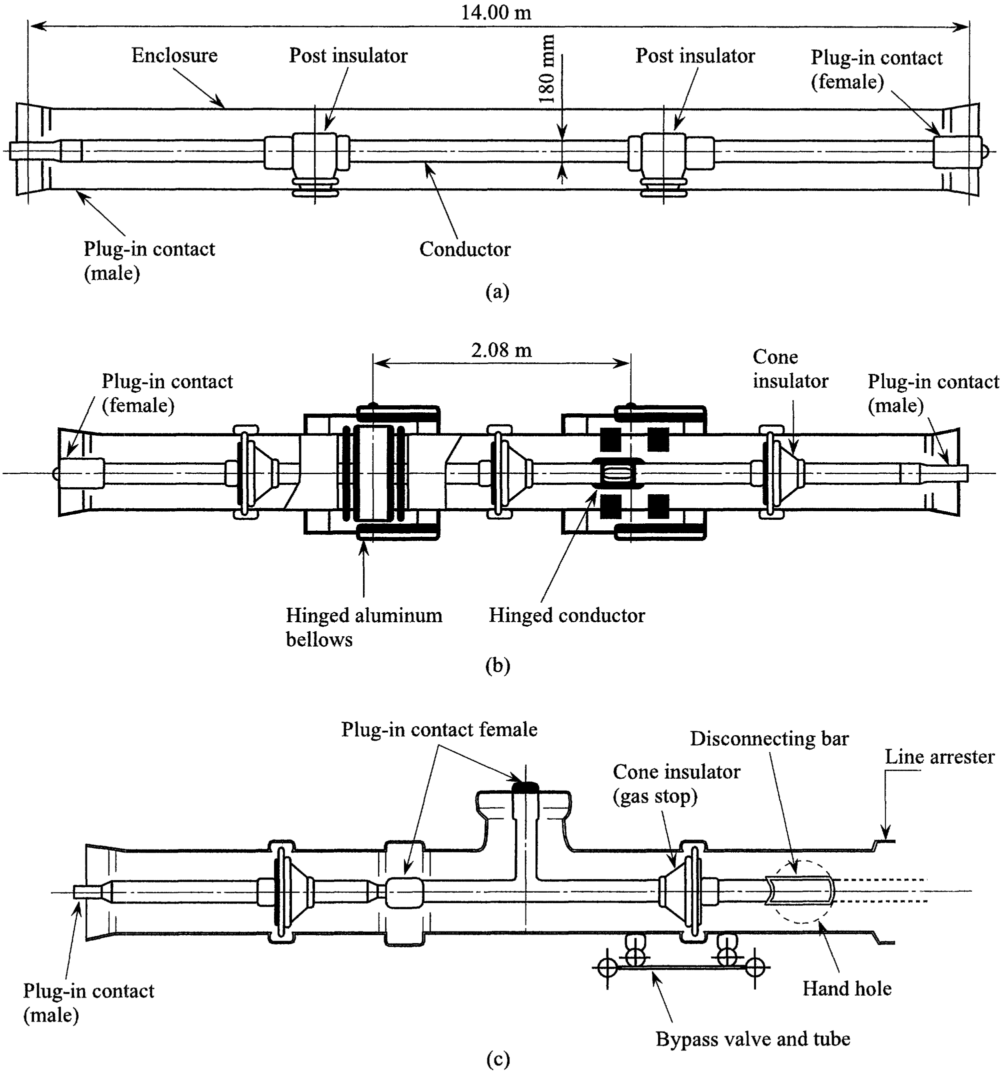


Figure 1.20 Typical sections of a compressed SF_6 gas power transmission cable: (a) straight section, (b) section with bellows, and (c) T-section (after [58]).

enclosure, partial discharges are initiated between the approaching particle and the site of its impending impact on the inner surface of cable pipe enclosure [61, 62]. In the presence of partial discharges, the SF_6 gas dissociates and reacts with oxygen to form some rather very toxic gases such as S_2F_2, SF_4, SO_2, SOF_2, and SO_2F_2. Although oxygen gas, which is required for some of the reactions to form the chemical radicals, may be available as a result of finite impurities in the SF_6 gas itself, it is much more likely to be provided by the traces of air adsorbed upon the surfaces of the components comprising the inner structure of the cable. The possibility of toxic gas production as well as the fact that SF_6 per se is a hot-house gas, coupled with data that indicates that gas leaks may and do indeed occur from the compressed cables themselves, have posed environmental concern. For this reason, there has been some effort directed toward possible replacement of the SF_6 gas by other gases, primarily gas mixtures such as nitrogen containing minute quantities of SF_6 gas. However, these gas mixtures have lower breakdown strengths than SF_6 and, therefore, entail the use of larger enclosure pipe diameters with attending increased costs.

The power transmission capacity of SF_6 cables is to a very appreciable extent also determined by their heat transfer characteristics [63]. The inner conductor operating temperature is usually within the range of 90–105°C. To prevent undue temperature rises within the gas cables, which may exceed the temperature limits of the epoxy resin spacer-insulators, the gas cable design must ensure an adequate heat dissipation rate by the cable envelope to its surroundings. The heat transfer from the inner conductor to the envelope is increased by application of black graphite paints over the surface of the conductor and the inner side of the tube enclosure. Since the heat transfer occurs by radiation as well as by convection within the SF_6 gas, it is much higher than for vacuum where heat transfer due to convection is nonexistent; consequently, the heat transfer rate is also increased with the pressure of the SF_6 gas. These considerations also indicate why vacuum insulated cables would experience difficulties in dissipating the heat generation at the surface of high current-carrying conductors. Since gas cables are normally installed outdoors and are unburied, the cooling of the external cable envelope itself occurs through radiation and external air convection. Thus, the wind direction and velocity have an important effect upon the cooling rate, and external heating of the envelope as a result of solar radiation must also be taken into account. However, installation of the gas cables at an angle to the horizontal ground plane appears to have only a minor influence [63].

Some work has been carried out toward developing nonrigid compressed SF_6 gas cables, since this would circumvent the incidence of particle contamination arising during cable part assembly in the field and provide the SF_6 cables with flexibility advantages inherent with conventional power transmission cables. In 1980, a flexible compressed SF_6 gas insulated cable design was described by Spencer et al. [64]. The cable, which is depicted in Fig. 1.21, is designed to operate at 362 kV and may have an overall length up to 80 m. The cable consists of a corrugated aluminum pipe as the outer conductor or shield and a multicore corrugated aluminium pipe as the inner conductor. It is expected that cables of this design may be operated at temperatures up to 140°C. Commercial equipment for the manufacture of flexible SF_6 gas cables has been made available in Germany. Since gas insulated cables have a higher characteristic impedance than oil-filled cables, they would be more susceptible to overvoltages when connected to the overhead transmission lines [12]. Accordingly, suitable protection must be provided. Although flexible SF_6 cables appear to have some practical advantages, no extensive use has been made of them thus far in the field.

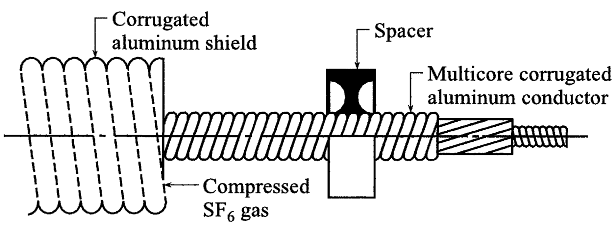


Figure 1.21 Flexible compressed SF_6 gas cable (after [13, 64]).

1.2.6.2 Superconducting Power Transmission Cables

Conceivably, compressed SF_6 gas cables should be capable of meeting any demand for larger capacity power transmission up to ~10 GW. However, this projection is perhaps valid only for the short term in view of increased environmental concerns with SF_6 gas and the associated attempts to constrain its use in electrical apparatus. In the long term the high power transfers are more likely to be accommodated with superconducting cables, which are characterized by low dielectric losses and extremely low resistive losses in their conductors. Although low-temperature superconductivity in metals at liquid-helium temperatures was discovered in the early 1900s, serious efforts to develop low temperature superconducting and cryoresistive cables were only undertaken in the late 1960s. With the discovery of high temperature ceramic superconductors in 1986, most of the development work on low-temperature metallic superconductors was abruptly halted because with high-temperature superconductors the cable operating temperatures can now be raised to 77 K or higher—thereby reducing very substantially the refrigeration costs. Nevertheless, at the present even if a reliable high-temperature superconductor cable design were achievable, it would be economically quite uncompetitive with comparable conventional cable systems designed to carry the same power load.

There were principally two concerted projects carried out on the development of low-temperature metallic superconductive cables, that have achieved tangible practical results. One was pursued at the Brookhaven National Laboratory [65] and the other at Arnstein in Austria [66, 67]. The Brookhaven prototype was a three-phase cable rated for 1000 MVA at 80 kV; the cable was tape insulated, thereby permitting the construction of a longer cable specimen length of 115 m. The superconductor was made of niobium-tin (Nb_3-Sn) and was applied in tape form as illustrated in the profile schematic of the cable construction in Fig. 1.22 [68]; the coolant used was helium. Other pertinent details on the superconductor are provided in Table 1.5. The prototype cable underwent extensive testing and evaluation at Brookhaven between 1982 and 1986 but was never installed in the field for in-service operation. Additional parametric data on the Brookhaven helium-impregnated tape insulated superconducting cable is provided in Table 1.6, from which it can be seen that the dielectric losses in the cable were less

TABLE 1.5 Nb_3Sn Superconductor Characteristics of the Brookhaven Low-Temperature Superconducting Cable

Overall tape thickness, 110 μm
Nb_3Sn thickness (total per tape in two layers), ~8 μm
Minimum bending radius (either direction), < 10 mm
Cable inner conductor diameter, 29.5 mm
Cable outer conductor diameter, 52.7 mm
Inner conductor tape width, 6.5 mm
Outer conductor tape width, 11.7 mm
Rated rms current at 60 Hz, 4100 A
Surface field at rated current (inner conductor), 44.2 A/mm
Mean current density (inner conductor), ~3700 A/mm^2
Critical current density at 4.2 K, ~6×10^4 A/mm^2
Operating temperature range, 6.5–8.5 K

Source: After [68].

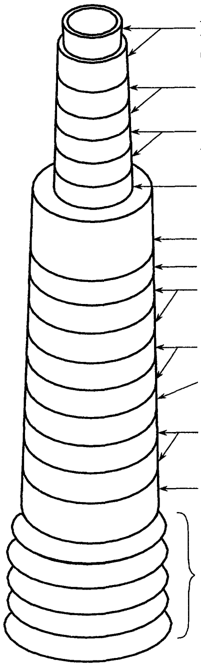


Figure 1.22 Flexible low-temperature superconducting prototype cable design at the Brookhaven National Laboratory (after [65]).

TABLE 1.6 Characteristics of Brookhaven Low-Temperature Superconducting Cable Prototype

Cable length installed (each), ~115 m
Cable outside diameter (over armor), 5.84 cm
Cryostat inner bore, 20 cm
Operating temperature, 7–8 K
Operating He density, 100 kg/m^3 minimum
Operating pressure, 1.55 MPa (225 psia) typical
Rated voltage (60 Hz), 138 kV, three phase
Rated current (60 Hz), 4100 A (continuous; 6000 A (60 min)
Operating voltage stress, 10 kV/mm
Operating surface current density, 44 A/mm
Maximum continuous power 1000 MVA (three phase)
Surge impedance load, 872 MVA (three phase)
Cable conductor loss at 4100 A (7 K), 0.2 W/m
Cable dielectric loss at 80 kV <0.06 W/m
Cable impedance, 25 Ω

Source: After [68].

than 0.06 W/m. In this design the dielectric performance characteristics are to a large extent determined by the coolant condition in the butt-gaps.

The first actual low-temperature superconducting cable installation was placed into service in Arnstein, Austria, in 1977. The cable operated in a superconducting mode at a voltage of 60 kV, employing a niobium film as the superconductor at liquid helium temperature with vacuum and liquid nitrogen employed for thermal insulation and helium-impregnated paper for electrical insulation. At the completion of the service trials in 1979, it was concluded that an upscaled cable of the same design could readily provide a load capacity between 2 and 3 GW [67]. Table 1.7 gives additional data on the Arnstein cable.

The only currently publicized low-temperature superconducting cable project still in progress is that in Japan [69]. The purpose of the study is to examine the behavior of solid extruded dielectric insulation (ethylene-propylene-rubber), which undergoes contraction as the cable is cooled down to cryogenic temperatures. Moreover, little is known on the degradation behavior of solid insulation at cryogenic temperatures, such as treeing.

The discovery of high-temperature ceramic superconductors has stimulated work to develop superconducting cables, which may operate at much higher cryogenic temperatures, hopefully with liquid nitrogen as the main coolant at 77 K. The first hurdle of producing a sufficiently pliable high-temperature superconductor for cables has been only recently surmounted. There are a number of high-temperature superconductors available, having a range of different transition temperatures, i.e., temperatures at which the conductor becomes superconducting [70]. Cable feasibility studies have been carried out using YBCO (yttrium-barium-copper-oxide) with a transition temperature of 90 K; however, this temperature is too close to the boiling temperature of liquid nitrogen (77 K), with the result that under overload or fault current conditions the temperature rise or swing of the cable conductor may be too large to restore the rated current of the high-temperature superconductor [71]. Thus, if YBCO is to be used as a cable conductor, liquid helium must still be employed to maintain the temperature rise of the conductor well below the temperature transition of 90°C for YBCO.

The high-temperature superconducting copper oxide ceramics per se do not have good flexibility characteristics and cannot carry high currents, nor can they withstand mechanical strains created by the Lorentz forces produced by the magnetic induction field and the current in the crystalline structure of the ceramic. High-temperature superconducting ceramic oxide wires are usually made by incorporating the superconducting filaments in a metal matrix, e.g., in the form of a tape having an approximate range of thickness that may extend from 200 μm to 0.2 mm with a width of 6 mm enclosed within a silver sheath [70]. The first step in the high-temperature superconductor wire-forming process is to synthesize a precursor powder, which may either contain the superconducting ceramic oxide initially or contain compounds from which the semiconductor can be produced by employing suitable mechanochemical processes. The precursor powder is then packed into a billet or tube, which is subsequently drawn into a wire. Following heat treatment, the wire is stacked into a bundle usually in the form of a tape in order to impart strength to the resulting multiwire ribbon. The high-temperature superconductor of bismuth-strontium-calcium-copper oxide ($Bi_2Sr_2Ca_2Cu_3O_{10}$), commonly referred to as BSCCO, has a transition temperature

TABLE 1.7 Arnstein Low-Temperature Superconducting Cable Characteristics

Voltage rating, 60 kV (three phase)
Cable length, 50 m (single phase)
Enclosure heat in-leak, 0.15 W/m (at 6 K)
Dielectric loss at 40 kV, 0.02 W/m (at 6 K)
Current rating, 1000 A

Source: From [67].

greater than 110 K and has been shown to be readily formed into longer wire lengths along with silver filaments for stabilization. The manufacturing procedure for the formation of BSCCO filaments is represented schematically in Fig. 1.23 [72]. In the process metal-oxide precursors of Bi_2O_3, $SrCo_3$, CaO, and CuO are reacted or calcinated at temperatures $\geq$ 800°C, followed by several cycles of grinding and reheating to form the BSCCO superconductor powder. The powder is subsequently packed into a silver billet, which is drawn through wire dies until its diameter is reduced to approximately 1 mm, whereupon a number of these wires are combined to form the desired tape conductor. The latter is then wound to the required conductor length and undergoes annealing in an oxygen furnace for a period of several days.

Although the BSCCO superconductor has exhibited great promise as concerns wire preparation, its performance at 77 K has been less impressive due to the low current densities that it can carry. Figure 1.24 depicts the critical surface for BSCCO formed by the temperature *T*, magnetic field, *H*, and the critical current density, J_c (the maximum current density, which the conductor can carry in the superconducting mode). As can be discerned from Fig. 1.24, the critical current density at the liquid-nitrogen temperature is only 5.4×10^2 A/mm^2 in the plane of the magnetic field at 77 K [73].

Notwithstanding the limitations of BSCCO superconductors, a prototype BSCCO superconductor cable was manufactured, using current oil-filled pipe-type cable technology and is depicted in Fig. 1.25 [72]. Liquid nitrogen is employed as the coolant. Detailed data on the cryogenic pipe-type cable is given in Table 1.8. A 120-kV SF_6 gas–liquid N_2 insulated cable termination for use in conjunction with a high-temperature superconducting cable for operation at 77 K has been recently described by Shimonosona et al. [73].

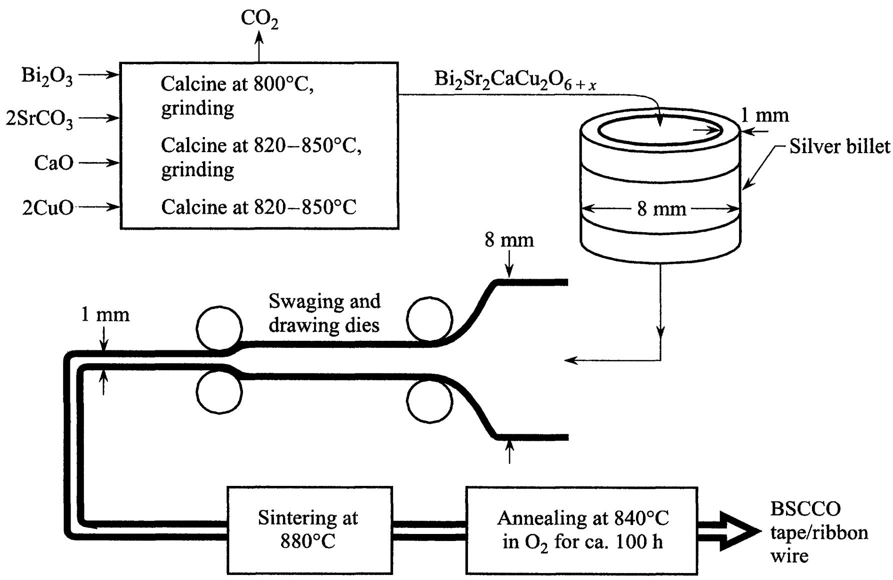


Figure 1.23 Processing steps for the preparation of the BSCCO high-temperature superconducting wire (after [72]).

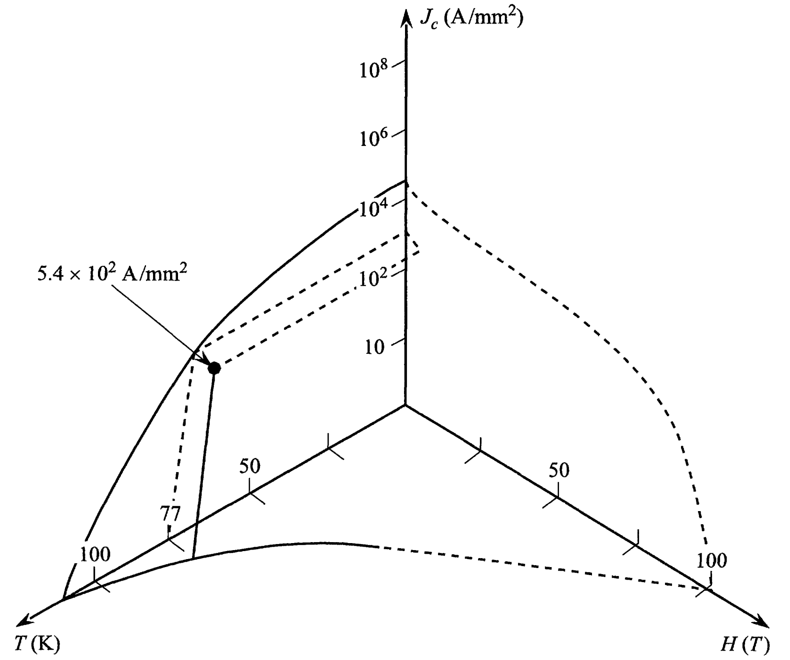


Figure 1.24 Critical surface of silver-sheathed bismuth-based high-temperature superconductor BSCCO (after [74]).

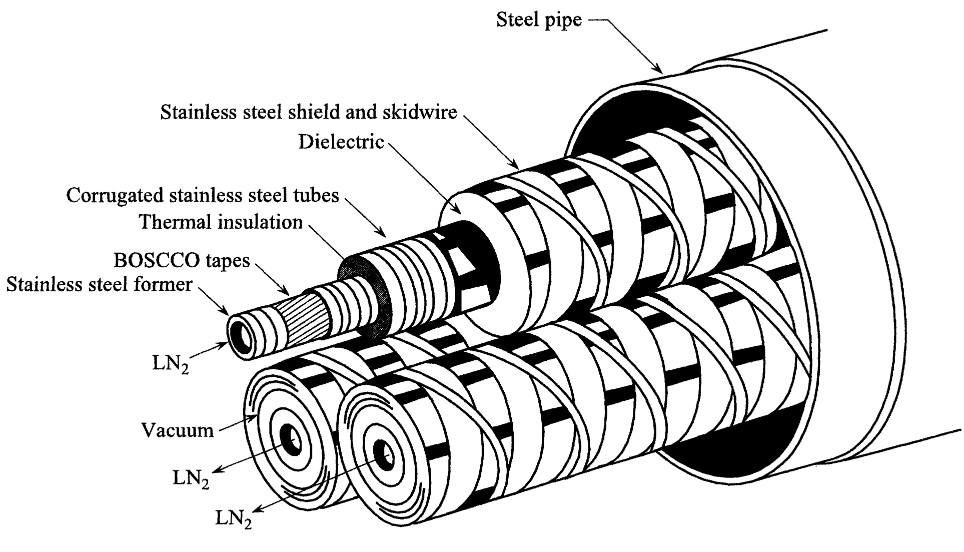


Figure 1.25 A 115-kV BSCCO three-phase high-temperature superconducting pipe-type cable (after [72]).

TABLE 1.8 Characteristics of 115-kV BSCCO Prototype Three-Phase High-Temperature Superconducting Pipe-Type Power Transmission Cable

Steel pipe diameter, 206 mm (8 in.)
Cable diameter in each phase, 85 mm
Cable length, 30 m
Power delivery capacity, 400 MVA
BSCCO silver-sheathed tape width, 4.5 mm
Number of BSCCO tapes in conductor, 150
Thermal insulation layer thickness, 12 mm
Total heat loss, 700 W/km MW

Source: From [69].

Figure 1.26 provides a schematic representation of possible power ratings either obtainable or anticipated with the different types of transmission cables available or contemplated in the future to meet the increasing electrical energy demand. It is apparent that much of the power transmission demand increase in the near future could conceivably be met by compressed SF_6 gas cables. However, for long-distance ($\geq$100 km) underground transmission applications with power transfers in excess of 10,000 MVA, cryogenic cables offer the only possible solution [75–77]. But in the context of present-day economics and the technical difficulties associated with maintaining cable stability at extremely high current densities, this solution is far from being a trivial one. For superconducting cables to gain access into the underground power transmission area, their manufacture, installation, and maintenance must be shown to be cost effective. Notwithstanding the optimism that has accompanied the appearance of high-temperature superconductors, it must be observed that from the technical point of view it still remains to be demonstrated that high-temperature superconducting cables can equal or surpass the performance achieved with experimental low-temperature superconducting cables. The area of high-temperature superconductors is shrouded by the fact that there appears to be no generally agreed theory to explain the different characteristics and behaviors of the various high-temperature supercon-

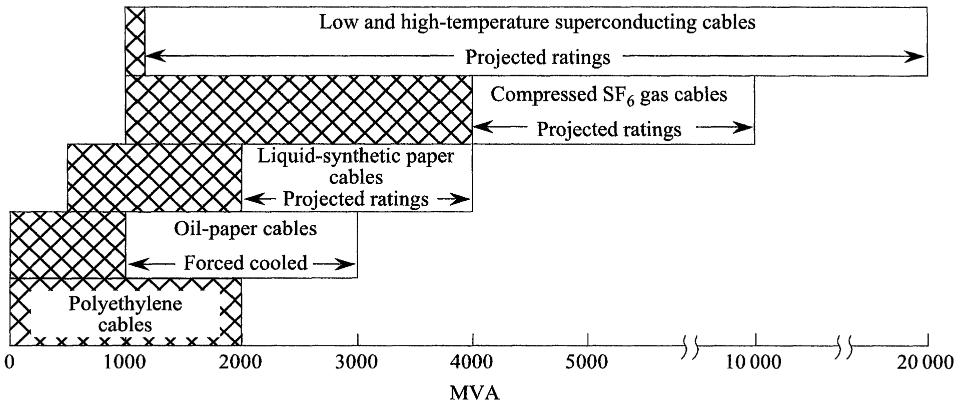


Figure 1.26 Ratings of present and possibly future power transmission cables.

ductors. It is only the YBCO that appears to fit well the accepted theory of superconductivity of the high transition temperature cuprates [78]. However, YBCO is atypical of the class of high temperature superconducting compounds, whose transition temperature to the superconducting state is frequently found to be highly sensitive to the preparation technique [79]. This to a large extent reflects the complicated metallurgical nature and chemical complexity of the high-temperature superconductors.

1.3 COMMUNICATION CABLES

1.3.1 Introduction

Communication cables trace their beginnings to telegraphy, shortly after the invention of the telegraph by Morse. The first successful telegraph cable was laid between Dover and Calais in 1851. Its success in continuity of service was attributed to the use of a reliable insulation, namely gutta-percha, and a protective steel armor; the cable employed copper conductors [80]. The experience derived from this cable pointed the way to the laying of the first trans-atlantic telegraph cable in 1866. Following the invention of the telephone by Bell, terrestrial telephone cables began to appear. The first telephone cable was installed in 1882, consisting of wires insulated with gutta-percha and natural rubber, which were plowed underground over a 5-mile stretch along a railway line [81]. The earliest telephone cables were essentially single-wire grounded lines [82]. The transmission characteristics of the rather rudimentary early telephone cables were improved substantially by adequately insulating the individual wires; however, over long distances cross talk as a result of capacitive coupling between adjacent pairs became a serious problem. In 1887, the introduction of lead sheath shielding of twisted pairs and (in 1889) the insertion of capacitors between the series of two separate circuits, for the purpose of capacitance balance, were effective in reducing significantly the cross talk.

Long-distance telephone transmission became a reality in 1906, when a 145-km cable, with inserted loading coils in order to further diminish the attenuation of the line, was installed between New York and Philadelphia; this was followed in 1910 with a 730-km line between Boston and Washington in which use was made of the quad arrangement whereby three circuits were formed from four wires; this resulted in a reduction of the total number of pairs for the number of voice circuits to be carried over the cable. The 1920s witnessed a significant decrease in the overall telephone cable diameters due to a reduction in the copper wire diameters, a further decrease in cross talk with staggered twisting of the wire pairs, and replacement of the lead sheathing with tin-lead and antimony-lead compositions. Over this epoch of the terrestrial communication cable development, the wire insulation was formed with paper ribbons. The porous structure of paper provided a low dielectric constant medium, thereby minimizing capacitive coupling between pairs.

Manufacture of paper-pulp-insulated wire cables began in the United States in the 1930s, which led to appreciable reductions in the space required per wire pair, thereby permitting a larger number of twisted-wire pairs per unit cable cross section. As in the case of paper ribbon cables, the wire gages employed were 22, 24, and 26 AWG (American Wire Gage), the notable exception being 19 AWG. Greater volumes of voice traffic during World War II and the postbellum period required larger cables with more twisted-wire pairs; for telephone cables containing 1800 pairs or more, the smaller diameter wires of 26 AWG size were employed. Concurrently, new cable sheaths of aluminum and different plastic materials were developed to replace the traditional but more expensive and heavier sheaths of lead alloys of tin, antimony, and cadmium. This allowed longer cable pulling lengths and resulted in greater ease of installation of aerial cables.

Plastic insulated twisted-wire multipair telephone cables first appeared in the 1950s and with rapidly decreasing cost of the plastic insulant (polyethylene or polyolefin) became quickly the twisted-wire multipair cables of choice. They have typically low installation and maintenance costs and are characterized by low dielectric losses. As a consequence of their lower attenuation characteristics, plastic insulated cables, commonly referred to as PIC cables, were employed initially for both long-distance analog transmission at carrier frequencies and subsequently for digital transmission, using pulse code modulation. The mutual capacitance between conductors in PIC cables, as for paper ribbon and pulp paper cables, was maintained at the accepted nominal value of 53 nF/km, and the PIC cables were manufactured with the same wire gage sizes as the antecedent paper-ribbon-insulated cables, i.e., including 19 AWG. At carrier frequencies to achieve lower attenuation, the 19 AWG larger diameter wire sizes were frequently employed; to obtain still lower attenuation, the wires were insulated with expanded polyethylene with which the mutual capacitance was reduced to 42 nF/km. Such lines were more economical in that fewer amplifiers or repeaters were needed to compensate for the attenuation losses.

The discovery of the thermoplastic polyethylene in the 1930s resulted not only in improved PIC twisted-wire cables but also provided an ideal flexible low dielectric loss medium for coaxial cables. Initial use of coaxial cables was made on electronic instruments and navigational applications as well as other military uses, principally in radar during World War II. It is interesting to note that the first coaxial submarine cable was installed between Havana and Key West in 1921; however, as this still occurred at a time prior to the discovery of polyethylene, the insulation consisted of gutta-percha. In Europe, a polyethylene insulated coaxial submarine cable was laid across the English Channel in 1947; its conductor was held in place by a solid polyethylene spiral tube, creating a partially air–solid dielectric insulating medium as depicted in Fig. 1.27 [80, 83]. It was shortly followed in 1950 by yet another polyethylene-insulated coaxial cable installation between Havana and Key West, along whose length repeaters were installed to amplify the transmitted signal. The first transatlantic coaxial submarine cable with repeaters and a rated capacity of 36 channels was installed shortly thereafter in 1956. With increased use of television, there developed in the 1960s a great demand for

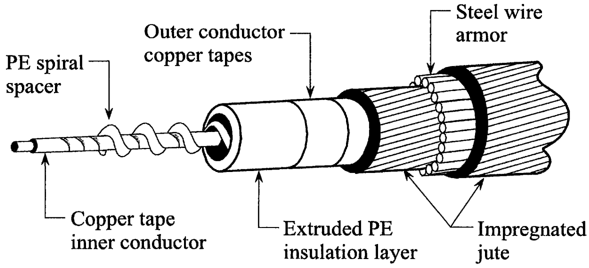


Figure 1.27 Early coaxial submarine cable with air-dielectric insulation, consisting of a polyethylene spiral spacer between the conductor and outer extruded polyethylene tube (ca. 1947) (after [83]).

coaxial cables with application to educational-TV, pay-TV, and community antenna TV (CATV) systems. For these uses low dielectric loss foamed or expanded polyethylene insulation was preferred. The CATV area has exhibited particular growth over the last few decades, and coaxial cable is still the preferred and most economic medium for transmission and distribution, though for long transmission distances increased deployment of optical fiber is now being made for backbone-trunk cables.

From the 1970s to the beginning of the 1980s, the air-dielectric coaxial-type cables dominated the long-haul telephone transmission field. The dielectric was principally air with intervening polyethylene disk spacers acting as supports for a solid copper inner conductor (7 or 10 AWG) within the coaxial cable. These cables replaced the twisted-wire multipair PIC cables, which could no longer meet efficiently the demands of the large volume of traffic, primarily due to the increased amount of data transmission along the cables whose original design had centered solely on voice transmission performance criteria. With digital transmission, using pulse code modulation and a repeater spacing of approximately 2 km, the maximum data rate transmission capacity achievable with air-dielectric coaxial cables was of the order of 400 Mbits/s. The mode of transmission in terrestrial coaxial cables was digital, using time division multiplexing (TDM) with pulse code modulation. This technique was introduced in the 1960s to replace the analog frequency division multiplexing (FDM) technique, which had dominated the telephone cable transmission field for approximately 50 years. The TDM technique was more effective in dealing with cross talk, signal distortion, and extraneous electrical noise. In contrast, however, the FDM technique remained the preponderant mode of transmission in long-distance underwater coaxial cables, including the last transatlantic coaxial submarine cable TAT-7 installed in 1983. It is important to emphasize that notwithstanding their structural differences in external armor or central strength member, all transatlantic underwater cables were insulated with solid polyethylene. A solid-polyethylene insulation was necessary to support a dc potential of several thousand volts, which was superimposed across the submarine coaxial cable to provide power to the signal repeaters placed along the cable.

The introduction of optical fiber telecommunication cables in the late 1970s revolutionized the communication cable field, since in these cables the transmission of voice and data information was accomplished via dielectric conductors in lieu of the traditional copper conductor wires. The eventual arrival of dielectric conductor communication cables was to be anticipated in view of Bell's photophone demonstration in 1880 [84] and the development of the theoretical basis underlying transmission along "dielectric wires" as described by Hondros and Debye in 1910 [85]. The realization of practical optical fiber cables required the development of low attenuation optical fibers and efficient light signal transmission sources and detectors. Reliable long lifetime semiconductor injection lasers for operation at room temperature were successfully designed in 1977 [86], though the early light sources used initially consisted of low power wide-frequency spectrum light-emitting diodes (LED); high-speed silicon *p-i-n* photodiode detectors became available in 1962 [87]. The development of silica fibers in 1970 led to what was at that time considered an acceptably low-loss transmission medium with an attenuation level of 20 dB/km at a transmission wavelength of 0.8 μm [88]. Even at these rather high attenuation levels, optical fibers represented an attractive transmission medium because of their instrinsically high transmission capacity. The use of optical fibers grew very rapidly following their introduction, and by the end of 1981 in Canada alone there were already 1500 km of installed optical fiber telephone cable, even though the attenuation losses in the early cables were as high as 4 dB/km as opposed to current monomode fiber cables with an attenuation of 0.2 dB/km at a wavelength of 1.55 μm.

The first transatlantic optical fiber telephone cable, having a data rate transmission capacity of 280 Mbits/s was laid in 1988. In this installation the transmission is carried out still with TDM, using electronic repeaters, which convert the optical signals to electrical signals for pulse shape regeneration purposes; after correcting for the attenuation loss, they are reconverted to optical signals before transmitting them along the cable. The vast majority of terrestrial optical fiber transmission systems are also operated in the TDM mode, and the latest long-haul lines have already achieved transmission capacities of 10 Gbits/s. With wave division multiplexing (WDM), the transmission capacity of optical fibers can be further augmented, and a commercial optical fiber transmission cable has already achieved a data transmission rate of 40 Gbits/s [89]. With erbium-doped optical fiber amplifiers, which are capable of simultaneous amplification of the transmitted optical signals using WDM transmission techniques, optical fiber transmission systems with a capacity of 0.1 Tbits/s are envisaged.

Following the introduction of optical fiber cables, there arose the perception and conviction that the rapid demise of copper conductor cables was imminent. Whereas this prediction was shown to be demonstrably correct as concerns the displacement of metallic conductor cables by optical fiber cables as the preferred transmission medium in the long-haul telephone cable area, it proved to be very much premature in the case of the local loop serving telephone subscribers and local area networks (LANs) such as Ethernet and IBM's Token Ring in which extensive use is still made of coaxial cables and twisted-wire pairs. Thus, at the present time, copper conductor communication cables are still being manufactured in large volumes to meet the demand for either new or replacement cables for short-distance voice and data transmission applications. The simple unshielded twisted-wire pair cable, which was originally designed for voice signal transmission, can now be operated over short distances at frequencies of several hundred megahertz with transmission rates up to 155 Mbits/s. Similarly, coaxial cables are now being made and used beyond their earlier 1-GHz limit. As long as metallic conductor communication cables remain cost-effective alternatives to optical fiber cables in meeting the necessary data transmission rate requirements, their use will continue for short-distance applications resulting in a continued proliferation of hybrid networks containing both metallic and optical fiber cable networks. In the sections that follow, we shall provide a cursory description of the types of communication cables currently in use in various application areas.

1.3.2 Twisted-Pair Communication Cables

In the field of telephone communications, it is customary to classify the cables into toll and exchange area cables. Toll area cables are employed for long-distance transmission, while exchange area cables comprise a category of cables that includes trunk, feeder, distribution, and video cables. Switching centers or central offices are connected by trunk cables, and feeder cables are used to connect the switching centers to the distribution areas from where the service drops to the subscribers are made with distribution cables. Video cables, as the name signifies, form the lines for picture signal links.

The early toll area or long-haul cables were of the multipair twisted-wire-type with either paper ribbon or paper pulp insulation. These were replaced with either regular

PIC cables of 19 AWG conductors with a mutual capacitance of 83 nF/mile or the low mutual capacitance (66 nF/mile) PIC cables. The latter also used twisted pairs with a conductor size of 19 AWG, but the twisted pairs were insulated with foamed polyolefin or polyethylene insulation, which required fewer repeaters as a result of their lower attenuation at carrier frequencies. The PIC toll area cables were replaced in the 1970s with composite multiple coaxial cables; the latter were subsequently themselves displaced from the long transmission link by optical fiber cables in the 1980s.

In North America, at the present, there are no multipair twisted-wire toll area cables in use; however, this is in contrast with the situation that prevails with exchange area cables serving the local subscriber loop. Trunk and feeder cables may consist of multipair twisted-wire polyolefin or polyethylene insulated PIC cables, having sizes of 900 pairs or less [90]. These cables may be filled with a jelly compound to prevent water ingress when buried or have an air-type core when used in aerial applications. The filling compound may be either petroleum jelly or an extended thermoplastic rubber (ETPR). Telephone cables, which are installed in ducts or directly buried, carry a protective polyethylene jacket and a metallic armor that may consist of aluminum, steel, and occasionally copper sheaths. In addition to providing mechanical protection, the metallic sheaths constitute effective electrostatic shields against induced voltages associated with lightning and, if properly sealed, prevent water ingress into the cable to avert increases in the mutual capacitance and possible shorts. At the distribution end, the service drop wire or distribution wire to the subscriber consists of two to six pairs; the buried distribution wire, in addition to a jacket, also carries a protective armor.

Figure 1.28 depicts schematically a twisted-wire pair telephone cable network serving a local loop. Since the late 1970s, the local loop networks were gradually converted from analog to digital carrier systems, which resulted in a substantial reduction in the number of twisted-wire pairs required in feeder cables. With digital transmission, the maximum length of a twisted-wire line usable without repeaters is contingent upon the

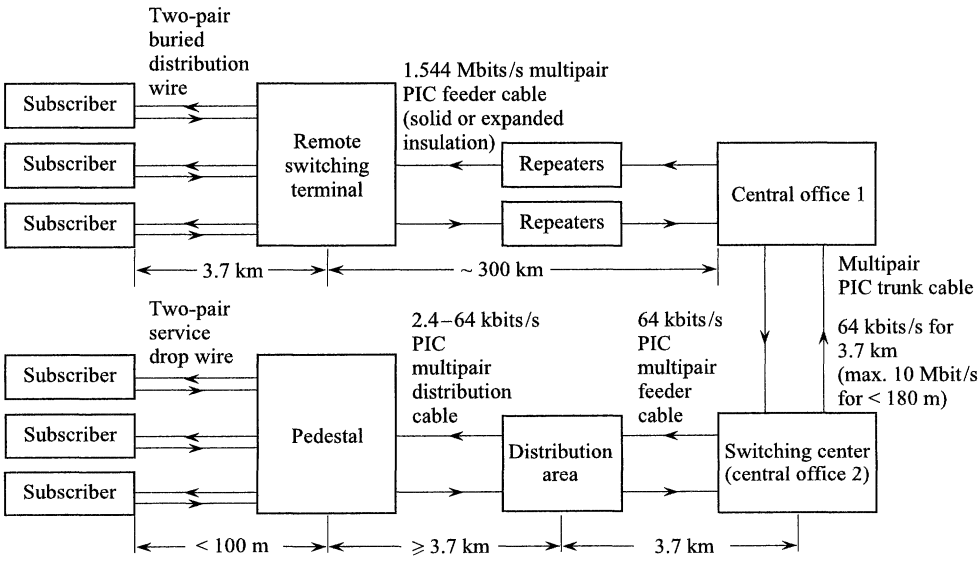


Figure 1.28 Multipair twisted-wire cables in the local loop.

gage of the copper conductor and the required data rate of transmission (cf. Chapter 15). For example, at a data rate of 2.4 kbits/s, the usable range of a 24 AWG wire pair is approximately 17 km without any repeaters; however, this value falls to approximately 2 km at a data rate of 1.544 Mbits/s. Most existing local loops provide data rate capacities up to 64 kbits/s without the use of repeaters for distances between 3.7 and 5.5 km between the central office and the distribution terminal. If repeaters are placed approximately 1.6 km apart along the feeder cable, then the distance between the central office and a remote switching terminal may be extended to several hundred kilometers. This antiquated long-distance PIC cable arrangement permits to increase the data rate to 1.544 Mbits/s and a corresponding increase in the number of subscriber lines at the remote switching terminal. As indicated schematically in Fig. 1.28, one twisted pair is employed for transmission and another for reception. The same data transmission capacity may be obtained, using high bit rate digital subscriber lines without the use of any repeaters with feeder cable lengths between the central office and the remote distribution terminal placed less than 3.7 km away. It is also interesting to note that the twisted-wire cable local loop network may be employed to transmit digital encoded video signals, using the asymmetrical digital subscriber line technique involving digital video signal compression methods at a rate of 1.5 Mbits/s within a closed loop less than 5.5 km.

Telephone cables, which are employed in the interior of buildings, e.g., central offices, commercial buildings, and subscriber homes, are classified as inside cables as opposed to all cables exterior to the building structures, which are denoted as outside cables. There are a number of salient differences between the two categories of cables. Station cable is a particular type of inside cable, since it is designed for both interior and exterior application [91]. It serves residences and consists of either two or four wire pairs with 22 or 24 AWG copper conductors as opposed to the normally larger inside cables, which are utilized in large commercial buildings and contain between 25 and 600 pairs of 24 AWG wire. Inside cables must comply with certain fire hazard regulations. Conductors of the wire pairs of inside plenum cables, which are installed in air circulating spaces (*plena*), are insulated with flame-retardant thermoplastics such as fluorinated ethylene propylene (FEP/Teflon) or ethylene chlorotrifluoroethylene (ECTFE/Halar). They may be extruded over the wire in either solid or expanded state as is also done with polyethylene or polyolefin insulation for cables for which the flame retardency requirements are less stringent. Because of its low cost and flame-retardant characteristics PVC is also used as an insulant, notwithstanding its higher dielectric constant and dielectric loss. Table 1.9 compares the properties of the various

TABLE 1.9 Properties of Electrical Insulating Materials Used in Multipair Twisted-Wire Telephone Cables

Insulation	Operating Temperature (°C)	Dielectric Constant	Oxygen Index (%)	Volume Resistivity (Ω-cm)
PE	60	2.3	18	10^{15}
ECTFE	150	2.5	64	10^{15}
FEP	250	2.0	93	10^{18}
PVC	60	3.7–3.9	28–41	10^{14}

Source: After [91].

insulating materials utilized on twisted-pair telephone cables. For inside cables, flame retardant jackets must be used and, as the oxygen index values in Table 1.9 indicate, FEP is the best flame-resistant material available albeit the most expensive.

A very large volume of twisted-wire pair cable is now used in LANs. These networks comprise communication systems with a specific topology that do not form part of the publicly switched telephone systems, though they are usually interconnected with them for outside communication. They are found in commercial buildings, manufacturing sites, military installations, laboratories, campuses of universities, airports, etc. One such system, originally introduced between 1984 and 1989, is the IBM Token Ring network, whereby unidirectional data is transmitted either at a 4- or 16-Mbits/s rate, using the protocol of a token, i.e., digital code word passing between data stations, whereby the station with the token is the one that is permitted to transmit [92]. The transmission medium may consist of either shielded or unshielded twisted-wire pair cables. With shielded twisted-wire pair (STP) cables, the distance between workstations may extend up to 200 m; if unshielded twisted-wire pairs (UTP) are employed, then the distance between the workstations is decreased and the number of the interconnected workstations is reduced from 260 to 72 [92]. Moreover, the error rate in the transmitted data is adversely affected in the absence of shielding. Table 1.10 gives typical maximum attenuation and near end cross talk (NEXT) values as a function of frequency for a two-pair shielded twisted-pair cable with a flame-retardant PVC jacket, which is suitable for use in the IBM Token Ring network. Flame-retardant expanded PE or expanded FEP insulation is used over a 22 AWG bare copper conductor. Each pair is individually shielded with an aluminum/polyester foil, followed by an overall tinned copper braid shield. It should be mentioned here that these high-performance metallic conductor cables are also acceptable for use between the terminal boxes and the workstations with the 100-Mbit/s FDDI (fiber distributed data interface) Token Ring network. Uniform spacing of conductors and their twisting into pairs and prevention of

TABLE 1.10 Electrical Characteristics of High-Data-Rate STP and UTP5 Cables

	STP 150 Ω, Two-Twisted-Pair Cable with Flame-Retardant Foam PE or FEP Insulation		UTP 100 Ω, Four-Twisted-Pair Cable with Polyolefin Insulation		
Frequency (MHz)	Maximum Attenuation (dB/m)	Minimum NEXT (dB)	Maximum Attenuation (dB/m)	Minimum NEXT (dB)	Minimum Return Loss (dB)
4	2.2	58	3.7	65	23
8			5.3	61	23
16	4.4	50	7.6	56	23
25			9.5	53	22
62.5			15.5	47	21
100	12.3	38.5	17.9	44	21
155			25.3	41	21
200			29.1	40	18
300	21.4	31	36.6	37	18
310			37.3	37	17
350			40.0	36	17

Source: Belden Wire & Cable Company

looseness of twists leads to substantial improvement in the transmission line characteristics of twisted-wire pair cables, permitting their use at increasingly higher frequencies or data rates. This improvement is evident particularly with the more recently manufactured high-grade unshielded twisted pair (UTP5) cables intended for high data rate cables, as classified in the ANSI/TIA/EIA 568-A, Category 5 standard. For comparison purposes, the electrical characteristics of a 350-MHz UTP5-type cable with a 24 AWG solid bare copper conductor insulated with polyolefin and covered with a low loss PVC jacket are tabulated in Table 1.10. The UTP5-type cables and their associated connector hardware are specified for data transmission rates up to 100 Mbits/s; with asynchronous transfer mode cell switching technology, their use may be extended to 155 Mbits/s.

From Table 1.10, it is apparent that the shielded twisted pairs, which are less susceptible to extraneous electrical noise and have typically a much more reduced radiated signal intensity, provide a significant improvement in the performance and signal transmission characteristics vis-à-vis the unshielded pairs. However, the lower cost of the latter presents the user with a compromising decision between economical and performance requirements. Shielded twisted-pair cables may also contain some unshielded pairs, but these are principally employed for voice communication circuits in the network. For the IBM Token Ring network, which operates either at 4 or 16 Mbits/s and which normally uses shielded twisted-pair cables, UTP5 should be more than adequate in view that even for the lower rated UTP3 and UTP4 cables the specified data transmission rate limits are already set at 16 and 20 Mbits/s. Figures 1.29 and 1.30 depict typical attenuation and NEXT characteristics of UTP3 and UTP5 cables, respectively.

The cable length between the multistation access unit is usually considerably less than the maximum permissible distance of 2 km in the IBM Token Ring network, which, as indicated, is a token-passing-type network; it consists of a closed-loop propagation medium in which hubs (automatic switches) or multistation access units (MAUs) are interconnected by means of a single 150-Ω shielded twisted-wire pair cable to form a ring as delineated in Fig. 1.31 [92]. To each hub are connected one or more workstations via shielded two-pair twisted-wire cables: one pair to receive the data and

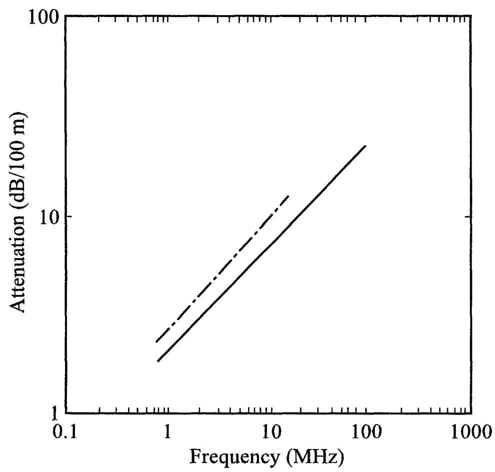


Figure 1.29 Typical attenuation characteristics of UTP3 and UTP5 type twisted-wire pair cables: — - —, UTP3 cable; —, UTP5 cable. (Courtesy of Belden Wire and Cable Company.)

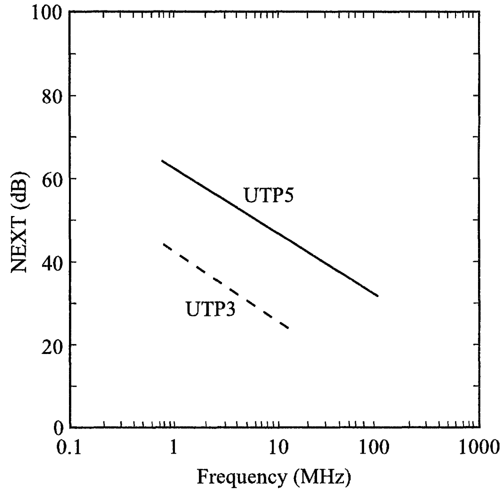


Figure 1.30 Typical near end crosstalk (NEXT) characteristics of UTP3 and UTP5 type of twisted-wire pair cables. (Courtesy of Belden Wire and Cable Company.)

another pair to transmit data. The hub, which acts as an automatic switch, senses when a station is on or off. If the workstation is off, then the switch shorts it out to maintain electrical continuity in the ring. If the workstation is on, the hub places the workstation in the ring circuit so that it can receive and transmit signals. As the token (digital code word) is circulated always in the same downstream direction within the ring, a station may capture it momentarily and then transmit the required data. Upon completion of the data transmittal, the workstation is obliged to pass the token along the loop whereby another workstation, which captures the token, may begin transmission. In this manner only one workstation can transmit data at a given point in time. In large cities with suburbs, in which commercial enterprises have a number of LANs operating over an extended area, the LANs are normally interconnected via optical fiber lines to form a metropolitan area network (MAN). Such networks may span across state, provincial, and international boundaries.

1.3.3 Coaxial Cables

The use of coaxial telephone cables attained its peak in the 1970s and early 1980s, when most of the long-haul telephone traffic in North America was carried via 75-Ω low-loss air-dielectric disk-spacer-type coaxial cables at a data rate of 274.176 Mbits/s. Thereafter their use rapidly declined as coaxial cables were replaced in the long-haul area by the less lossy optical fiber lines. Their 40-year dominance in the long-distance submarine telephone cable area came to a rather abrupt end in 1988 with the installation of the first transatlantic optical fiber telephone cable. However, the T4 (44.736 Mbits/s) telephone cable system functions with coaxial cables, and some coaxial cable may still be found in the local loop of the telephone system. But, at the present, the most extensive fields of coaxial cable usage continue to be those of CATV and certain LANs.

Community antenna television has become a well-established service that, shortly after World War II, has been distributing television programs via coaxial cables directly to the subscriber's premises. Initially, its operations were confined to rural regions where TV reception could only be obtained by means of antennas erected on high

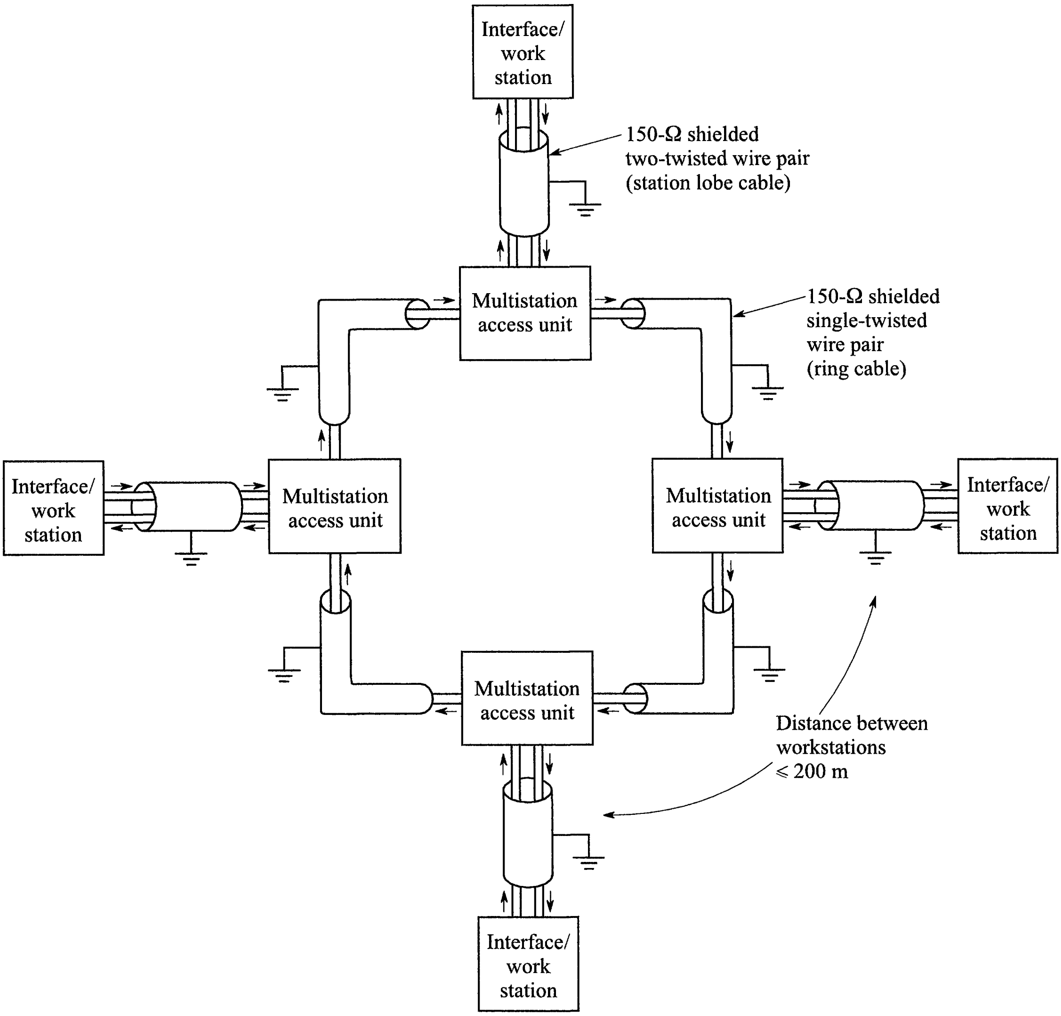


Figure 1.31 Simplified schematic of IBM Token Ring LAN network interconnected with 150-Ω shielded twisted-wire pair type cables [92].

aclivities or towers; eventually, however, in the 1960s, it began serving large urban populations, providing high-quality reception of channels otherwise not available in certain localities. Present CATV systems receive their television signals from geostationary communication satellites by means of approximately parabolically shaped dish-type antennas at the cable head (receiving end), from where the signals are transmitted and distributed to the subscribers.

The first CATV systems employed solid polyethylene insulated-type RG-11 coaxial cables with copper braid shielding obtained from military surplus, which became available after World War II [93]. The need to transmit video signals over relatively large areas within cities and their suburbs led to the development of low-loss coaxial cables; 75 Ω was selected for their characteristic impedance, because of its proximity to 77 Ω, which represents the minimum attenuation criteria in a coaxial cable (cf. Chapter 15).

Initially, CATV provided three channels from the low end of the very-high-frequency (VHF) band of 54 MHz up to 88 MHz. With the introduction of the ultra-high-frequency (UHF) TV broadcast band, the upper frequency limit was extended to 550 MHz and, finally, to 750 MHz as a result of further improvements in the electronic distribution equipment [93]. The upper bandwidth of 750 MHz, which already accommodates an analog video channel capacity of more than 100 channels, may be augmented by a further factor of 10 by means of digital video compression techniques. With the current wide-band analog equipment in the home, subscribers may receive 77 analog channels within the 54–550 MHz band; in the future, digital audio and video services will be offered within the 550–750 MHz band.

As already mentioned, the CATV system, because of the relatively longer transmission distances, required the development of low-loss coaxial cables. Low attenuation requirements necessitated the use of 75-Ω characteristic impedance cables in lieu of the traditional 50-Ω coaxial cables normally employed in instrumentation work; in addition, the losses are further decreased by utilizing foamed or expanded polyethylene insulation, having lower insulation conductance and permittivity than an equivalent solid-polyethylene coaxial cable. For trunk and feeder cables, a continuous aluminum sheath, which forms the outer conductor of the coaxial cable, is extruded over the foamed insulation. The diameter of the outside aluminum conductor of the cables is at least 0.5 in. and may even exceed 1.0 in., depending upon the size of the inner copper conductor, since the characteristic impedance is a function of the inner and outer conductor radii. However, the size of the inner conductor must be sufficiently large to carry the current to provide power to the amplifiers along the coaxial line. The aluminum sheath conductor is rigid and minimum bending radii are specified to prevent sharp bends, which may cause changes in the impedance along the coaxial line, e.g., an aluminum sheathed coaxial cable of 0.75 in. outside diameter has a minimum bending radius of approximately 7.5 in. The aluminum-sheathed coaxial cables, if placed in direct burial, must be protected against corrosion; this is accomplished by an extruded polyethylene covering over the Al sheath/shield.

The smaller diameter feeders on distribution cables, which branch off the larger diameter trunk cables, carry the TV signal to the local area of the cable TV subscribers. The coaxial drop cable, from the coaxial distribution cable to the service entrance of the dwelling, is a flexible cable and it may differ in construction depending upon the length of the drop distance. To maintain complete shielding of a flexible coaxial drop cable, aluminum-coated polymer tapes are frequently employed. Since the drop cable is most frequently aerially suspended, a copper-coated steel inner conductor is employed to provide built-in strength for the cable; also additional reinforcement may be obtained by means of a galvanized steel messenger wire. The latter is incorporated in the jacket such that the cross section of the overall cable assumes the form of a figure of 8. Coaxial service drop cables that are buried have foils applied over the shielding braid to prevent moisture ingress and protect against corrosion. These types of construction are illustrated in Fig. 1.32. All shown cable specimens have an identical construction, except that the coaxial cable, portrayed in Fig. 1.32(c), which is intended for direct burial applications, has a low-molecular-weight polyethylene grease film applied under its jacket to prevent water ingress and subsequent aluminum shield corrosion should mechanical damage of the jacket take place; a low-density polyethylene jacket is employed in lieu of a PVC jacket to provide a softer and more flexible cable at low temperatures. The laminated shielding tape, which consists of a polyester film

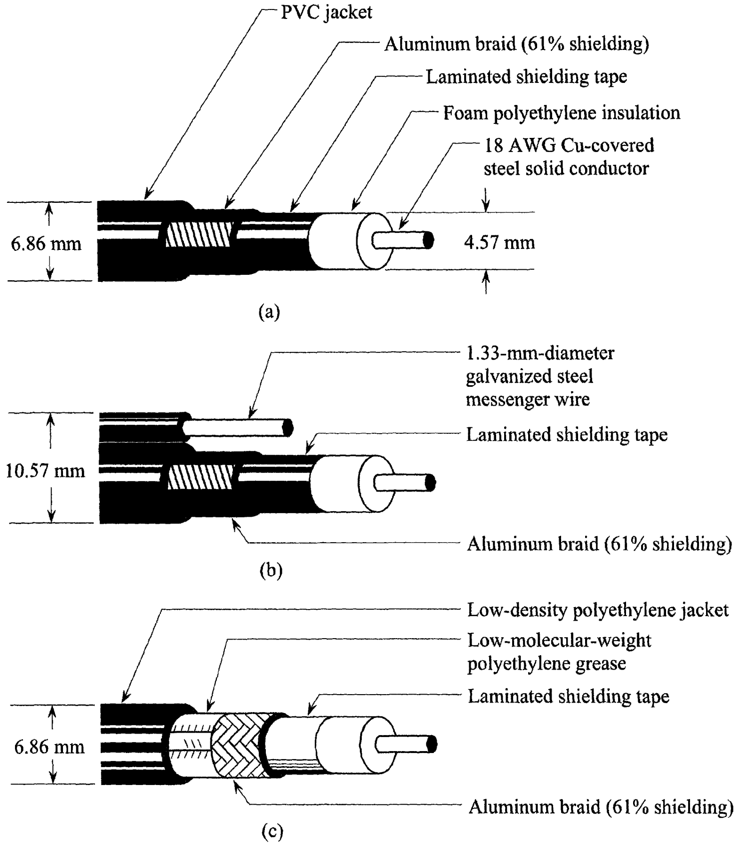


Figure 1.32 CATV type RG-6/U 75-Ω coaxial drop cables (a) aerial cable, (b) aerial cable with reinforcing messenger wire, and (c) cable for direct burial. (Courtesy of Belden Wire and Cable Company.)

sandwiched between two aluminum foils with an adhesive on one side of one of the aluminum foils to ensure bonding to the insulation, is applied longitudinally over the insulation. This ensures effectively 100% shielding over the coaxial cable, which renders the cable less susceptible to extraneous interference and reduces as well the radiated interference from the cable itself. In this respect, the drop cables are shielded as effectively as the trunk and feeder coaxial cables with the continuous but less flexible extruded aluminum sheath. The coaxial drop cables have a minimum structural return loss (SRL) of 20 dB; their velocity of propagation is equal to 82% of the speed of light, which is essentially the same as that in the feeder and trunk cables, whose insulation also consists of foam polyethylene.

The CATV tree topology network originates at the head end of the trunk cable, where the encryption equipment is located and the TV signals that are received from a satellite by means of a quasi-parabolic dish antenna are amplified prior to their transmission along the rigid foam polyethylene insulated aluminum-sheathed coaxial cable (cf. Fig. 1.33). The outside diameter of the aluminum sheath is ≥ 0.75 in. and may in some instances even exceed 1.0 in. If direct buried, the coaxial trunk cable is protected

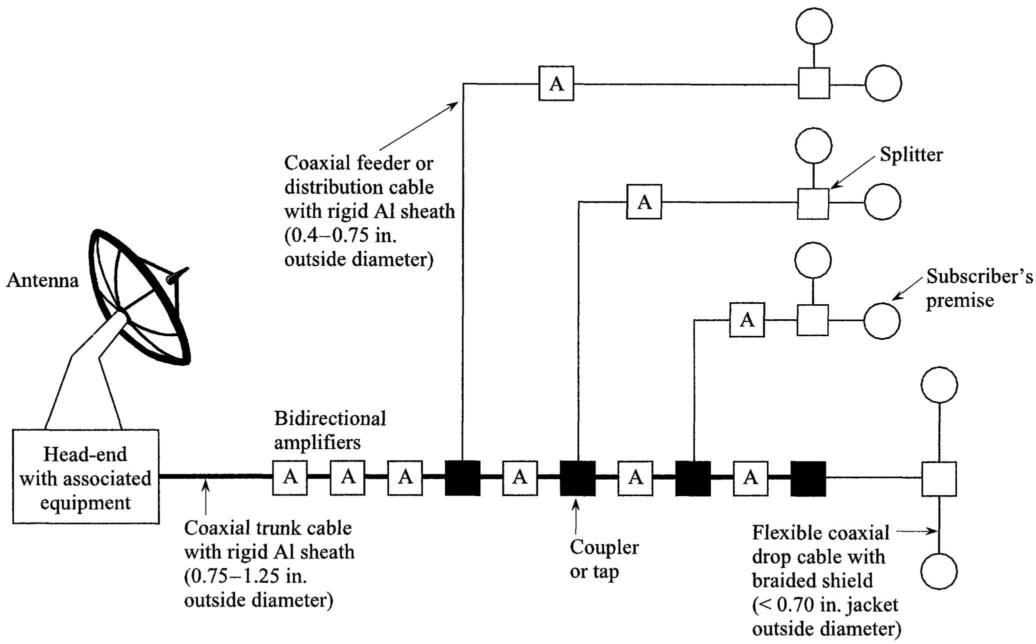


Figure 1.33 Simplified schematic diagram of CATV system.

against corrosion by means of a polyethylene jacket. The trunk cable has amplifiers inserted along its length at approximately 0.5-mile intervals, up to a maximum of 40 amplifiers [93]. By means of equalizers these amplifiers compensate for the increased attenuation at the more elevated frequencies (cf. Table 1.11). The signal levels are maintained using automatic gain control in the amplifiers; an ac current is supplied along the conductor to meet the power requirements of the amplifiers. The feeder or distribution cables include also amplification equipment, and as mentioned previously they are similar in construction to the trunk cables but have a substantially smaller aluminum conductor outside diameter, usually between 0.50 and 0.75 in. The flexible coaxial drop cables at the customer end are of the type shown in Fig. 1.32. The trunk cables may have lengths between a few miles up to approximately 30 miles with an attenuation range extending from 0.7 to 1.2 dB/100 ft at 300 MHz for the coaxial

TABLE 1.11 Attenuation Characteristics of CATV Drop Cables

Frequency (MHz)	Attenuation (dB/100 ft)	Frequency (MHz)	Attenuation (dB/100 ft)
5	0.45	400	4.21
55	1.53	450	4.47
211	3.02	550	4.95
270	3.44	750	5.83
300	3.64	870	6.30
350	3.93	1000	6.78

Source: Belden Wire and Cable Company.

cables aluminum sheath outside diameters ranging between 0.75 and 1.0 in. [93]. The shorter feeder cables, with outside diameters between 0.4 and 0.5 in., have attenuation values between 1.2 and 2.0 dB/100 ft; the still smaller 0.25-in.-outside-diameter drop cables are usually characterized by attenuation values in the range of ca. 3.5–6 dB/100 ft and a nominal pulse delay of 1.2 ns/ft. Table 1.11 gives the attenuation characteristics for frequencies between 5 MHz and 1 GHz of the CATV coaxial drop cables delineated in Fig. 1.32.

In a CATV system, two transmission paths are required: one for the inbound and another for the outbound signal. The outbound signal contains the TV programs for the subscriber, whereas the inbound signal (within the subband of 5–30 MHz) is used to obtain information from the subscriber end such as that on program billing [93]. This may be achieved by means of either a dual-cable configuration or a split configuration; the former technique [94], because it entails the use of two cables, presents an increased cost. The split configuration, delineated schematically in Fig. 1.33, necessitates the deployment of bidirectional amplifiers, which pass the lower frequency inbound signals and the higher frequency outbound signals with respect to the head end along a single coaxial cable. The frequency band of the outbound signals in most current CATV systems is within 50–550 MHz as opposed to 40–300 MHz, which characterized the earlier systems [94]. The splitters, inserted between the distribution and drop cables and shown in Fig. 1.33, divide the signal power in half, i.e., each subscriber receives half of the power from the distribution cable. Thus, a four-way splitter arrangement would permit the connection of four subscribers. The couplers or taps between the trunk and feeder or distribution cables simply divert a fixed amount of signal power from the trunk cable into the feeder cable.

The use of bidirectional amplifiers along a trunk cable in a CATV system adds to the maintenance costs of the overall system. Accordingly, in some CATV systems the coaxial trunk cables have been replaced with optical monomode fiber trunk cables, which can be operated without any amplifiers over distances up to 30–40 km due to their intrinsically low attenuation of ca. 0.4 dB/km at a wavelength of 1.31 μm. However, with such hybrid fiber–coaxial cable systems, the trunk portion of the cable must now have two separate optical fiber cables i.e., one for the inbound and another for the outbound signal [93].

A local area network in which extensive use of coaxial cable is being made is the Ethernet, which was introduced first by Xerox in the 1970s [95, 96]. Although recent versions of the Ethernet are now utilizing twisted-wire pairs, there are many coaxial cable connected Ethernets in service considering that the Ethernet is by far the most prevalent and popular LAN deployed because of its high speed, low cost, and widely available software and peripherals. The Ethernet topology is specified in the Institute of Electrical and Electronics Engineers (IEEE) 802.3 standard, with its protocol based on the carrier sense multiple-access with collision detection (CSMA/CD). The workstations in the Ethernet may be connected via interfaces to a coaxial cable bus as depicted in Fig. 1.34. The individual workstations monitor continuously the data transmission on the coaxial cable bus and transmit only when the cable is inactive. Should two or more workstations decide to transmit simultaneously, then this collision will be detected and the workstations will then attempt to retransmit subsequently their data at some randomly selected time interval [95].

The Ethernet employs coaxial cable that may be wired either with the so-called thick or thin coaxial cables, with both media capable of providing a maximum data

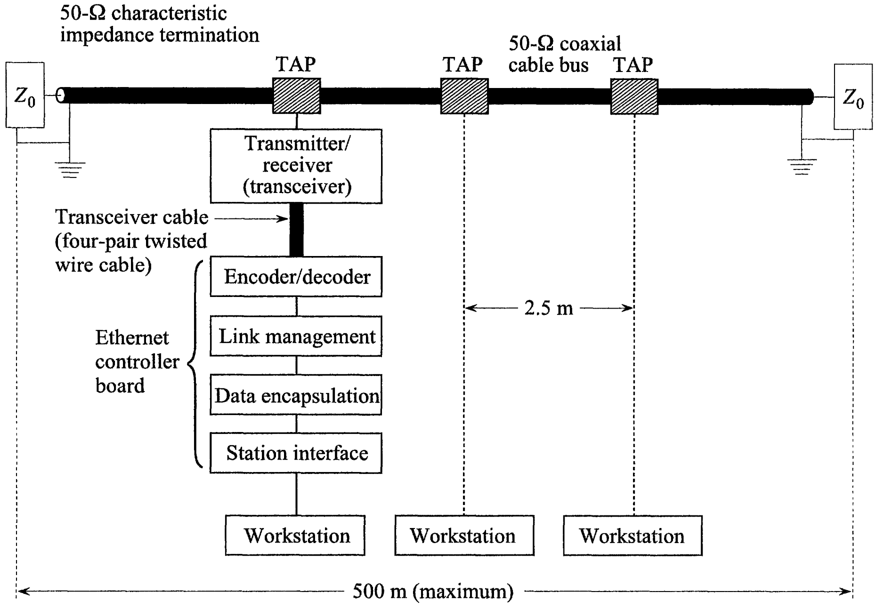


Figure 1.34 Ethernet topology with thick coaxial cable bus (IEEE 802.3, 10 Base 5) (after [94]).

transmission rate of 10 Mbits/s. The thicker or larger outside diameter coaxial cables, with a correspondingly larger conductor, can support a bus length of 500 m as opposed to the thinner or smaller outside diameter coaxial cables whose length is limited to 200 m [94]. The IEEE 802.3 standard refers to these two types of coaxial cable installations as 10 Base 5 and 10 Base 2, respectively; the term Base denotes a base-band system, i.e., because in base-band transmission the signal is sent without any modification, the system may be used either for digital or analog transmission. Both the thin and thick coaxial cables have a characteristic impedance of 50 Ω, since with digital signals the 50-Ω cable is preferred because it is less susceptible to signal reflection introduced by the insertion capacitance associated with the taps (interfaces); 50-Ω coaxial cables are also less affected by low-frequency electromagnetic interference than are the less lossy 75-Ω coaxial cables, which constitute the medium of choice for broadband applications in CATV systems [94].

The coaxial cable bus is terminated in its characteristic impedance of 50 Ω at both ends to prevent data interference due to reflections from the two cable ends. The workstations are connected to the coaxial cable bus via taps, with the separation between taps being fixed at 2.5 m to prevent phase addition of reflections between taps [94]. The maximum number of workstations is determined by the number of taps, which is usually set at approximately 100. The transceiver shown at the taps in Fig. 1.34 senses the presence of signals in the coaxial cable bus, recognizes whether there is a collision between two signals, and, respectively, transmits and receives signals to and from the coaxial cable bus in accordance with the CSMA/CD protocol. An important function of the transceiver is that of ground isolation between the signals of the workstation and those on the coaxial cable bus to avert differences in ground potential that may result in large cable shield currents, that may introduce noise as well as pose safety-related problems [94]. The transceiver cable is a specially designed four-pair shielded cable, which connects the Ethernet controller board to the transceiver and supplies power to the transceiver; the controller board's intelligence circuitry regulates the communication over the Ethernet. Although this section is devoted specifically to the discussion on coaxial cables, the importance of the transceiver or attachment unit interface drop cable in the Ethernet warrants its description here; it is depicted in schematic form in Fig. 1.35. It comprises four twisted-wire pairs with tinned copper conductors insulated with polypropylene, each pair shielded with a reinforced metallic foil, covered overall with a polyester tape, followed by a metallic foil–plastic composite tape and then a copper braid of 92% shielding effectiveness. The overall cable contains a 24 AWG stranded tinned copper drain wire, and the cable is protected by a PVC jacket. One twisted-wire pair in the transceiver cable has stranded tinned 24 AWG copper conductors and supplies power to the transceivers. The remaining three pairs with 28 AWG conductors are 78-Ω signal cables terminated in their characteristic impedance at both the transceiver and the network card of the personal computer (PC); one pair is employed for data transmission and another pair to receive data. The third pair is utilized either to transmit 10-MHz signals to the workstation whenever the transceiver detects a collision of data on the coaxial cable bus or a short burst of the 10-MHz signal to indicate the end of data transmission by a workstation. The transceiver itself is attached directly onto the coaxial cable bus by means of a sharp penetrating clamp that makes direct contact with the center conductor of the coaxial cable bus.

The so-called thin coaxial cable Ethernet uses smaller diameter coaxial cables, which are easier to manipulate and install. As a consequence, notwithstanding the reduced length of the thin coaxial cable bus (200 m) as compared to that of the thick coaxial cable bus (500 m), the use of the thin coaxial cable Ethernet is much more prevalent. Figure 1.36 depicts a typical thin Ethernet-type coaxial cable, which is specifically designed for use on the Ethernet coaxial cable bus. It consists of a 20 AWG tinned standard copper interior conductor insulated with foam polyethylene, shielded with a laminated Al-polyester-Al tape with a heat-sensitive adhesive applied on one of its sides, followed by a tinned copper braid of 93% shielding effectiveness and a PVC jacket. This particular cable is rated for a maximum temperature of 80°C. Cables rated for higher temperatures (150°C) use FEP (fluorinated ethylene-propylene, Teflon) insu-

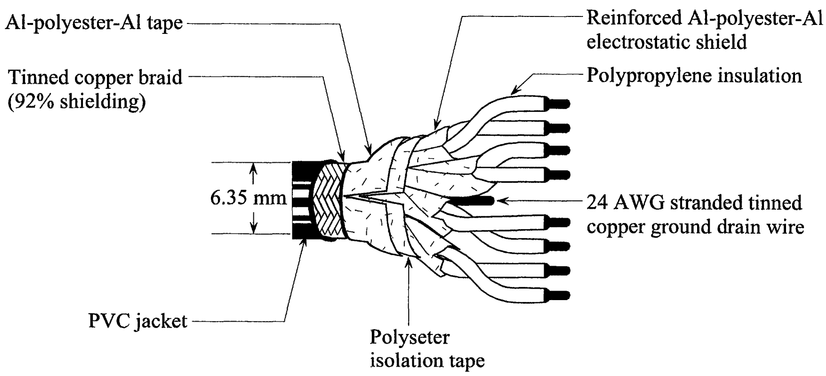


Figure 1.35 Four-pair twisted-wire transceiver cable; the stranded tinned copper conductors of one pair are 24 AWG, while the three remaining pairs of 78-Ω impedance have 28 AWG conductors. (Courtesy of Belden Wire and Cable Company.)

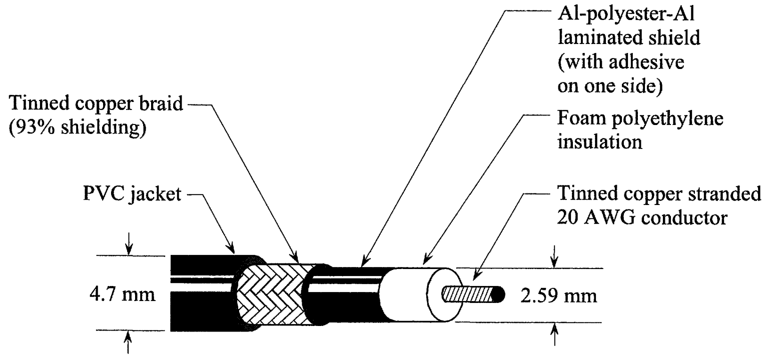


Figure 1.36 Ethernet thin coaxial bus cable, IEEE 802.3, 10 Base 2. (Courtesy of Belden Wire and Cable Company.)

lation and fluorocopolymer jackets. The attenuation characteristics of the Ethernet thin coaxial cable are given in Table 1.12. Comparison with Table 1.11 shows that the attenuation values of the Ethernet thin coaxial cable are significantly higher than those of the Ethernet thick coaxial cable, which accounts for the shorter permissible length of the Ethernet thin coaxial cable bus.

Over the many years of extensive use since its introduction in 1970, the Ethernet has become the most popular of the LANs; it has continued to mutate into forms, that have increasingly become more cost effective principally as a result of the replacement of the coaxial cables by twisted-wire pairs. The earliest Ethernet using twisted-wire pairs, which was introduced in the 1980s, was confined to a low data transmission rate of 1 Mbit/s, though it still maintained a maximum bus length capability of 500 m [95]. This antecedent technology is covered under the IEEE 1 Base 5 standard. The extension of the Ethernet to a data rate of 10 Mbits/s for twisted-wire pair connection entails the use of UTP3, 4, or 5 grade twisted-wire pair cables; this twisted-wire pair system is covered by the IEEE 10 Base T standard, which significantly reduces the distance capability of the network to a length of 100 m. The high data rate standard IEEE 802.3, 100 Base X defines a 100-Mbit/s network, which uses category UTP5 wiring and is limited to a distance of 150 m [96]. Another 100-Mbit/s capacity network is covered by the IEEE 802.12, 100 VG standard and uses HP (Hewlett-Packard)

TABLE 1.12 Attenuation Characteristics of a 50-Ω Ethernet Thin Coaxial Cable

Frequency (MHz)	Attenuation (dB/100 ft)	Frequency (MHz)	Attenuation (dB/100 ft)
1	0.43	100	4.2
2	0.60	200	6.1
5	0.90 (0.99 max.)	400	8.9
10	1.30 (1.40 max.)	700	12.1
20	2.00	900	13.9
50	3.00	1000	14.8

Source: Belden Wire and Cable Company.

technology; it is similar to the 100 Base X network in that a four-pair UTP3 wire system is employed in lieu of a two-pair UTP5 wire system in order to permit the higher data transmission rates with lower grade twisted-wire pairs. However, the maximum permissible bus length is consequently reduced from 150 to 100 m.

The 10 Base T, 1 Base 5, 100 Base X, and 100 VG networks, all of which use twisted-wire pairs, have a physical star-type topology; i.e., each workstation is connected directly via a twisted-wire pair cable to a hub or concentrator, which either simply connects the wiring together and passes the signals between the workstations (passive hub) or regenerates the signals prior to passing them (active hub) [95, 96]. Thus, if a problem develops with the cables of a given workstation, it only poses difficulties with the specific workstation involved and does not affect the performance of the other remaining workstations. However, the connections of the hub are configured logically so that each workstation forms part of a single logical bus as in the case of the coaxial Ethernet bus [92]. Thus, the maximum given twisted-wire cable lengths correspond to the cable lengths between the workstation and the hub as opposed to the actual length of the coaxial bus in the Ethernet wired with coaxial cable. A 10-Mbit/s optical fiber Ethernet (10 Base F) allows hub-to-workstation optical fiber cable lengths up to 4 km, thereby permitting the interconnection of workstations situated in different buildings spaced up to several kilometers apart.

Another important application of coaxial cables, dating from the 1950s has been in TV broadcast network studios. These cables bear considerable similarity to CATV cables in that they have a characteristic impedance of 75 Ω and use foam insulation, though where more flexibility is required, solid-polyethylene insulation is employed; in the solid-dielectric construction, the velocity of propagation is reduced to 66% of that of light in free space. The high-performance requirements for these studio cables usually necessitate the use of dual shields. Since the earlier mode of transmission of color video signals entailed the transmission of the picture information in analog form while the synchronizing signal information was in digital form, the design of video cables evolved into a form that was suited both for analog and digital signals. As a consequence, following the introduction of digital broadcasting in the early 1980s, coaxial cables have become an important transmission medium for digital video signals. Figure 1.37 portrays a typical coaxial video cable construction rated for a maximum temperature of 80°C which has a dual shield consisting of aluminum foil–polyester–aluminum foil

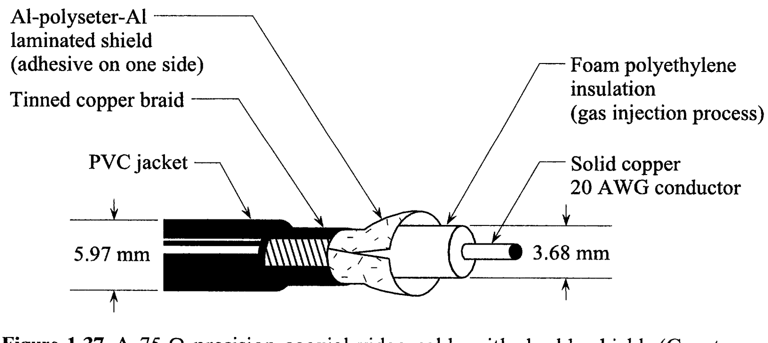


Figure 1.37 A 75-Ω precision coaxial video cable with double shield. (Courtesy of Belden Wire and Cable Company.)

laminates with a 100% shielding effectiveness followed by a copper braid of 95% shielding effectiveness. The attenuation characteristics of this cable are given in Table 1.13; its velocity of propagation is typically 83% of that of the speed of light, a value characteristic of foam-type polyethylene insulation.

1.3.4 Optical Fiber Cables

Optical fiber systems have several decisive advantages over the usual type of metallic conductor communication cables; these advantages reside primarily in their unusually high bandwidth capacity and their nonmetallic construction that renders them immune to electromagnetic interference and dangerous fault currents in the vicinity of electrical power lines. Although present coaxial cable systems may have bandwidths up to 1 GHz and additional bandwidth improvements resulting from the use of multiplexing and coding techniques, the bandwidths inherent with current commercial optical fiber cables, using modulated light transmission, have already achieved the 40-GHz level.

An optical fiber cable comprises a fiber core, which consists of silica, glass, or plastic material that may be clad with silica, glass, or plastic having a slightly lower index of refraction to ensure that the light waves are propagated along the core. Thus, the optical line acts essentially as a waveguide along which the optical signal is transmitted; the signal is launched by means of pulse-code-modulated LED device or laser sources and received by means of semiconductor light detectors (photodiodes). Attenuation and pulse dispersion are the two prime parameters affecting information data transmission rate in optical fiber cables. Several factors influence attenuation losses: (i) material absorption losses caused by a variation of the index of refraction of the material as a function of wavelength, e.g., these losses may arise in glass fibers from the presence of any transition metal ionic impurities and OH^- ions; (ii) material scattering losses as a result of density changes and structure variations within the fiber material itself; (iii) any fiber bending losses; which give rise to radiation losses; and finally (iv) waveguide scattering losses, which appear because of minute irregularities at the core and cladding interfaces. Protection against impurity ingress into the fiber's core and cladding is provided by a plastic coating applied over the cladding that also imparts mechanical strength to the fiber. The occurrence of pulse dispersion in optical fiber cables imposes limits on their data rate capacity and bandwidth. It is caused by intermodal, material, and waveguide dispersion mechanisms in the optical fibers [97].

TABLE 1.13 Attenuation Characteristics of a 75-Ω Precision Coaxial Video Cable, Whose Construction Is Described in Fig. 1.34

Frequency (MHz)	Attenuation (dB/100 m)	Frequency (MHz)	Attenuation (dB/100 m)
1	0.95	400	15.4
10	2.9	700	21.0
50	5.9		
100	7.9	900	23.9
200	10.8	1000	25.6

Source: Belden Wire and Cable Company.

As a result of the successful development of low-loss silica fibers at Dow Corning, optical fiber communication technology has become essentially a silica-based technology, and higher loss plastic materials are now only utilized for very short connection applications where high cable flexibility is required. Various forms of pure and doped silica are employed, with the silica cores having an index of refraction ≤ 1.48 and the cladding a correspondingly slightly lower value. The selected transmission wavelengths, within the infrared spectrum, in optical silica fiber cables are 0.85, 1.3, and 1.55 μm. The two latter are chosen because they are situated on the opposite sides of the major OH^- ion resonance absorption peak at two attenuation minima of the silica fiber. The value of 0.85 μm also evades some minor OH^- peaks, but falls in a relatively high attenuation region of the silica fiber over which the losses arise predominantly from Rayleigh scattering mechanisms. However, this transmission wavelength was used in the early multimode fiber telephone cables in the 1970s and early 1980s, because it coincided with the region of emission of the A1GeAs laser and LED light sources [98].

There are three types of silica optical fibers employed in communication cables, namely the multimode step index, multimode graded index, and single or monomode fibers. The multimode step index fiber was the fiber employed in the first optical fiber telephone cables installed in the 1970s (cf. Chapters 15 and 17). The relatively large core diameter of 50 μm in the early cables (with a cladding diameter of 125 μm) permitted easy termination and coupling of these fibers. Primarily broad spectrum modulated LEDs were utilized as light wave sources, and the cables consisted of relatively short spans operating at low data transmission rates at the wavelength of 0.85 μm. These cables were characterized by a relatively high attenuation of ≤ 4 dB/km, and their useful transmission distance was limited by their inherently high pulse dispersion caused principally by intermodal dispersion, which was intrinsically associated with the different length of paths of the various modes of light wave propagation within the multimode fiber as illustrated in Fig. 1.38. It is apparent from Fig. 1.38 that the number of modes within the multimode fiber is determined by the launch angle of the light signal with respect to the axis of the fiber; evidently, a light signal transmitted along the axis of the fiber will take the least time to reach the detector at the far end of the fiber. For a fiber of length ℓ_0, this minimum time of travel will be simply given by

$$t_{\min} = \frac{\ell_0}{v} = \frac{\ell_0 n_1}{c} \tag{1.1}$$

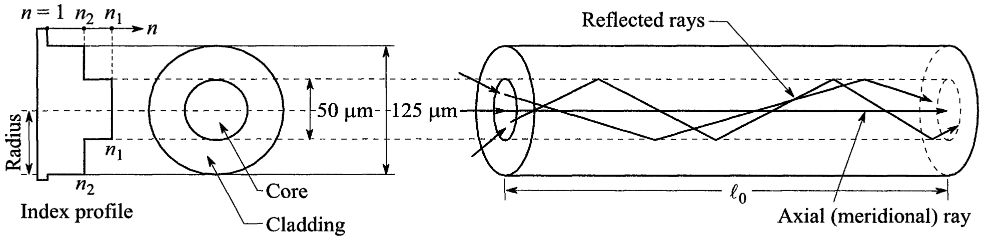


Figure 1.38 Transmission of light rays along a step-index multimode optical fiber.

where υ is the velocity of the light signal in the fiber whose index of refraction is n_1 and c is the velocity of light in free space. The longest time of travel, t_{max} will occur when the light signal enters the optical fiber at the critical angle just sufficient for reflection to occur; if the length of the path of travel for this signal is equal to ℓ, then t_{max} is given by [99]

$$\begin{aligned} t_{max} &= \frac{\ell}{\upsilon} \\ &= \frac{\ell_0(n_1/n_2)}{(c/n_1)} \\ &= \frac{\ell_0 n_1^2}{c n_2} \end{aligned} \tag{1.2}$$

where n_2 is the index of refraction of the cladding. Thus, a digitally transmitted square pulse along a step-index multimode fiber will be broadened by an amount

$$\begin{aligned} \Delta t &= t_{max} - t_{min} \\ &= \frac{\ell_0 n_1}{c}\left(\frac{n_1}{n_2} - 1\right) \end{aligned} \tag{1.3}$$

Since pulse dispersion associated with intermodal dispersion is expressed in nanoseconds per kilometer length of cable, Eq. (1.3) may be rewritten in the form,

$$\frac{\Delta t}{\ell_0} = \frac{n_1}{c}\left(\frac{n_1}{n_2} - 1\right) \tag{1.4}$$

for multimode step-index optical fibers; the quotient of $\Delta t/\ell_0$ is in the order of several tens of nanoseconds per kilometer, which imposes a limit on the useful transmission length of the fiber as well as the frequency of the input signal.

The idea of using a graded refractive index for the core to reduce intermodal dispersion in multimode optical fibers was first conceived in 1964 [100]. But more than a decade elapsed before such fibers were developed; this involved the doping of the silica core to produce a paraboloid-like distribution structure in the index of refraction in which the index diminished gradually from its maximum at the center of the core to a value equal to that of the cladding at the core-cladding interface. In this manner the speed of the light rays is reduced at and in the vicinity of the center of core as a result of the higher index along the shorter paths and increased toward the edge of the core due to the lower index of refraction along the longer paths. This results in all rays arriving almost simultaneously at the signal receiving end. Figure 1.39 illustrates schematically light wave propagation along a graded-index multimode fiber.

The grading of the core index in multimode fibers reduces the intermodal dispersion to well below 10 ns/km, which may even in some circumstances approach those of single-mode fibers. Both multimode and monomode fibers are subject to additional pulse dispersion as a result of material and waveguide dispersion. Waveguide dispersion is dependent upon the geometry of and the material comprising the waveguide as well as the frequency spectrum of the light source; that is the signal propagation velocity

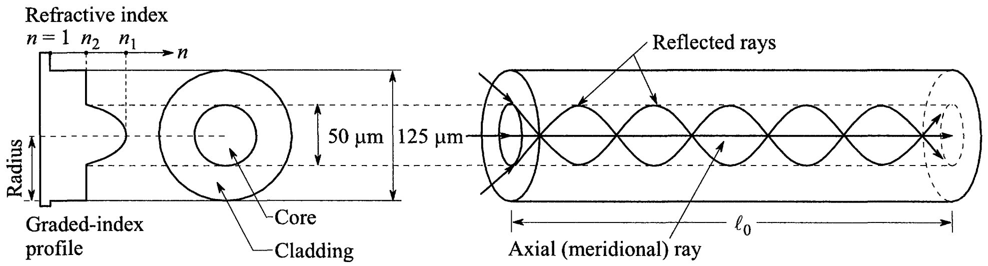


Figure 1.39 Transmission of light rays along a graded-index multimode fiber.

varies with the wavelength. The material dispersion, which arises as a result of the dependence of the refractive index upon wavelength (associated with atomic and molecular resonance absorption phenomena), is thus also dependent on the frequency spectrum of the light source. The effect of the light source upon the material and waveguide dispersions of the fiber is taken into account by expressing the dispersion caused by both phenomena in the units of picoseconds of pulse broadening per kilometer of fiber length per nanometer of light source spectral width (ps/km-nm) (cf. Chapters 15 and 17). Since the material and waveguide dispersion versus wavelength characteristics of doped silica fibers have slopes of different signs, a net zero dispersion point is found to occur on the wavelength scale and is evinced at 1.3 μm. It is for this reason that many of the early multimode fibers telephone cables, which have been initially placed in service for operation at 0.85 μm using the more economical but wider spectrum LED incoherent light sources, have been changed over to operate at the zero dispersion wavelength of 1.3 μm. Even for relatively short lengths of multimode fiber operating at 0.85 μm, the material and waveguide dispersions can give rise to pulse dispersions of nearly 100 ps/km-nm thereby imposing serious constraints on the data transmission rates that these cables are able to sustain.

The first installation of a long-distance multimode fiber telephone cable operating at the zero dispersion wavelength of 1.3 μm was effected in 1982 [98, 101]. In the application use was still made of an LED source to transmit over a cable distance of 205 km with repeaters placed a maximum of 10.3 km apart. The data transmission rate over this long-haul telephone cable was 34 Mbits/s. When the LED sources are substituted with coherent light-emitting laser sources having narrower spectral widths and more power output, longer lengths of multimode fiber cable may be used with correspondingly augmented repeater spacings. This approach was first demonstrated in 1987 with an inter-exchange trunk multimode fiber cable operating with a laser source at 1.3 μm over a distance of 42 km without repeaters [98, 102]. The system was capable of a transmission rate at 45 Mbits/s; the receiver consisted of a GaAs-FET preamplifier and *p-i-n* photodiode, which was characterized by a fast response time to the incident light energy.

Present graded-index multimode fibers, which are primarily employed in local area networks, have attenuation characteristics that in the limit may be made to approach very closely those of single mode fibers that have typically values of ~2.0 dB/km at 0.85 μm, <0.3 dB/km at 1.3 μm, and <0.2 dB/km at 1.55 μm. Commercially available graded-index multimode fibers have bandwidths up to 1 Gbit/s-km that may be extended to values as high as 6 Gbits/s-km when produced experimentally under highly controlled conditions in contrast to step-index multimode fibers whose bandwidth, as a result of severe intermodal dispersion, may be significantly below 50 Mbits/s-km. Note that the unit of bandwidth for optical fibers is expressed as a data rate or frequency-distance product, implicitly indicating that the bandwith is a quantity dependent upon the length of the fiber. For example, should a particular optical fiber of 1-km length have a bandwidth of 50 Mbits/s-km, then for a repeaterless distance of 10 km, its bandwidth would necessarily be reduced to 5 Mbits/s-km. Frequently bandwidth units for optical fibers are also stated in kilohertz per kilometer, megahertz per kilometer, gigahertz per kilometer, etc., with hertz substituting for the date rate unit of bits per second.

Commencing with 1981 concertive efforts were undertaken to evaluate the performance of high bit rate monomode optical fiber cables at the transmission wavelengths of 1.3 and 1.5 μm [98, 103–105]. The experimental work, which was directed toward the development of long-haul terrestrial and submarine monomode optical fiber cable systems, demonstrated that data transmission rates between 140 Mbit/s and 2 Gbit/s were readily attainable with monomode fibers with repeater spacings of 100 km [98, 103–109]. This led rapidly to the design and manufacture of long-haul monomode optical fibers, culminating in 1988 with the laying of the first transatlantic optical fiber submarine cable with a data transmission rate capacity of 280 Mbits/s at the wavelength of 1.31 μm (cf. Chapter 17).

Most of the early single-mode or graded-index monomode optical fiber telephone cables were designed for operation at the wavelength of minimum dispersion, i.e., 1.3 μm. Their operation at the attenuation minimum, occurring at the wavelength of 1.55 μm, was precluded because of the sizable material dispersion of 18 ps/km-nm manifest at the same wavelength. But with the development of dispersion-shifted single-mode optical fibers, whereby the refractive index profile of the fiber is modified in order to alter the waveguide dispersion behavior such that the wavelength of the material and waveguide dispersion cancellation is transposed from 1.3 to 1.55 μm, the dilemma has been resolved. There are still many older long-haul single-mode fiber cables operating at 1.3 μm, but the more recent installations of long-haul single-mode fibers are dispersion shifted (index profiled) for operation at 1.55 μm in conjunction with narrow spectrum 1.55 μm laser sources and detectors (cf. Chapter 15).

In single-mode optical fibers, the prevailing intermodal dispersion that typifies the behavior of step-index multimode fibers, is eliminated by restricting the diameter of the core to $\leq 10\,\mu m$, so that the core size becomes too small to support a multimodal propagation process. As portrayed in Fig. 1.40, the single-mode fiber design also

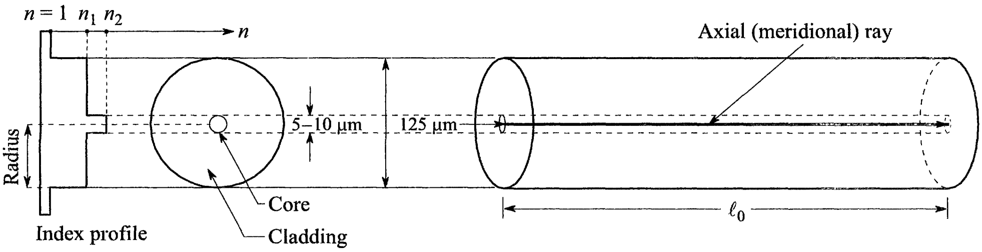


Figure 1.40 Transmission of light rays along axis of a single-mode fiber.

utilizes a step-index profile. The index of the single-mode fiber core may be typically ~1.460 (n_1) as compared with that of 1.457 (n_2) for the cladding [110]. By comparison, the corresponding values for both the step-index and graded-index multimode fibers are typically $n_1 = 1.470$ and $n_2 = 1.455$; i.e., the refractive index of the core, n_1, for both the step-index and graded-index multimode fibers is the same except that in the case of the graded-index multimode fiber n_1 represents only the maximum value of refractive index at the center of the core.

A single-mode or monomode fiber allows only one mode (the lowest order mode) to propagate at a given wavelength, the condition for this being that the radius of the core is to be less than twice the wavelength emitted by the laser source. Consequently, the core diameters of monomode fibers are by a factor of approximately 10–6 times smaller than those of multimode fibers. Optical fiber cables are characterized by their numerical aperture (NA), which is equal to $(n_1^2 - n_2^2)^{1/2}$; physically, it is a measure of the spread of a light beam emitted from the end of an optical fiber placed a distance d away from a screen mounted perpendicularly to the axis of the fiber. With this type of arrangement, it is defined by the term $2r/d$, where $2r$ is the diameter of the circular projection on the screen launched from the end of the fiber. The numerical apertures of multimode fibers are typically between 0.21 and 0.23, while those for single-mode fibers are at least a factor of two less. The value of the numerical aperture is important as it determines the coupling efficiency between the laser or LED light sources and the input end of the fiber. However, for long-distance transmission small values of NA such as those intrinsic to single-mode fibers are required to avert intermodal dispersion. Figure 1.41 depicts a typical single-mode optical fiber long-haul submarine cable. Note the extensive armor protection provided for the optical fibers, including the hermetically sealed copper tube to prevent moisture ingress into the cable. The cable is designed for operation at 1.550-1.565 μm and contains three single-mode fiber pairs (i.e., six fibers). Each pair is designed to carry eight channels, with each channel operating at 2.5 Gbits/s.

Virtually all of the long-distance multimode and monomode fiber telephone cables installed between 1980 and 1996 are operated using electronic repeaters in conjunction with electronic time division multiplexing (TDM). The repeaters optoelectronically regenerate and amplify the optical signals, which become attenuated and distorted as they travel along the optical fiber lines. The repeaters convert the optical signals into electronic signals, which are in turn amplified, reshaped, and retimed. The emerging signals, which have essentially a reconstructed form almost identical to the original electronic signals, are subsequently applied to drive a semiconductor laser whose output provides a train of optical pulses having the same magnitude and form as the original optical pulse at the input to the fiber line. Since the electronic repeaters add a very substantial expense to the optical transmission line, lower attenuation and pulse dispersion lines with longer repeater spacings are desirable. The improvement in the attenuation and pulse dispersion characteristics of optical silica fiber cables over the past 18 years has resulted in appreciable gains in the data transmission rate capacity of commercial optical fiber telephone cables as indicated in Fig. 1.42; the solid curve represents the gains made by cables operated using TDM, with a maximum capacity of 10 Gbits/s being attained in 1996 [89]. The isolated point of 40 Gbits/s for the year 1996 refers to cables operated using wave division multiplexing (WDM), which is analogous to the frequency division multiplexing (FDM) transmission method used with multipair twisted-wire cables, except that with optical fibers it is being carried

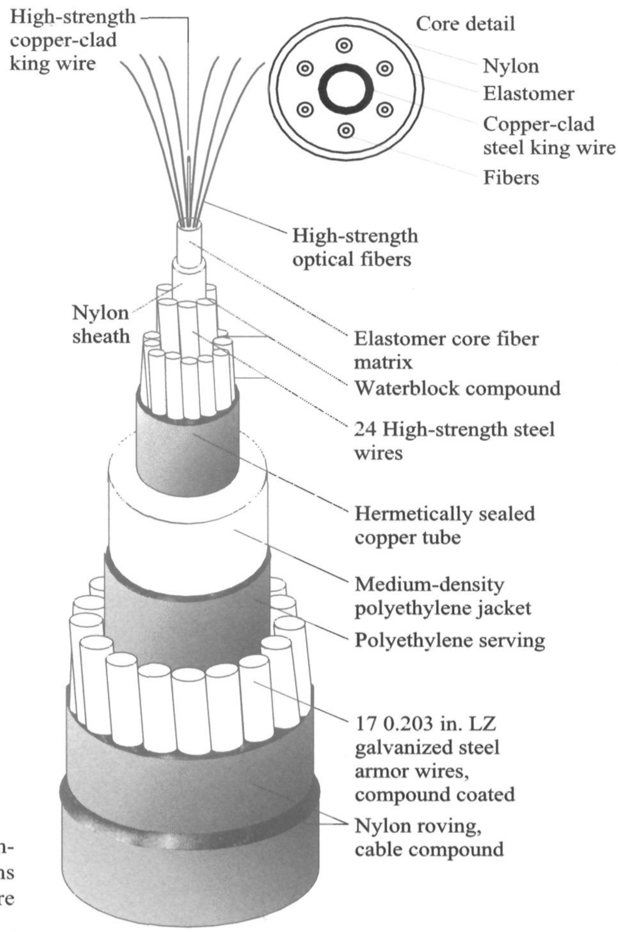


Figure 1.41 A 42-mm-outside-diameter single-mode optical fiber telecommunications submarine cable. (Courtesy of Simplex Wire and Cable Company.)

out in the optical frequency domain (cf. Chapter 15). The maximum data transfer rate capacity achieved thus far experimentally with WDM is placed at 2 Tbits/s [89]; the enormously large capacity potential with optical fibers using WDM is thus palpably apparent.

The early optical telephone transmission cables were characterized by their low transmission rate capacities, which in the case of step-index multimode fibers were limited by both their relatively high attenuation as well as their intermodal dispersion characteristics. With the development of graded-index multimode fiber cables, pulse broadening was reduced to an acceptable maximum range of values between 1.0 and 2.5 ns/km. These multimode cables, which had core and cladding diameters of 50 and 125 μm, respectively, were designed to operate in the temperature range between −40 and 60°C, being thus suitable for application in the Northern Hemisphere. Their attenuation values were still in the range of 4.0 dB/km at 0.85 μm and 2.5 dB/km at 1.3 μm, hence their useful length was essentially attenuation limited and relatively short repeater spacings of ~12 km were required in pulse-code-modulated systems with laser sources. Increasingly higher transmission rate capacities were achieved following the

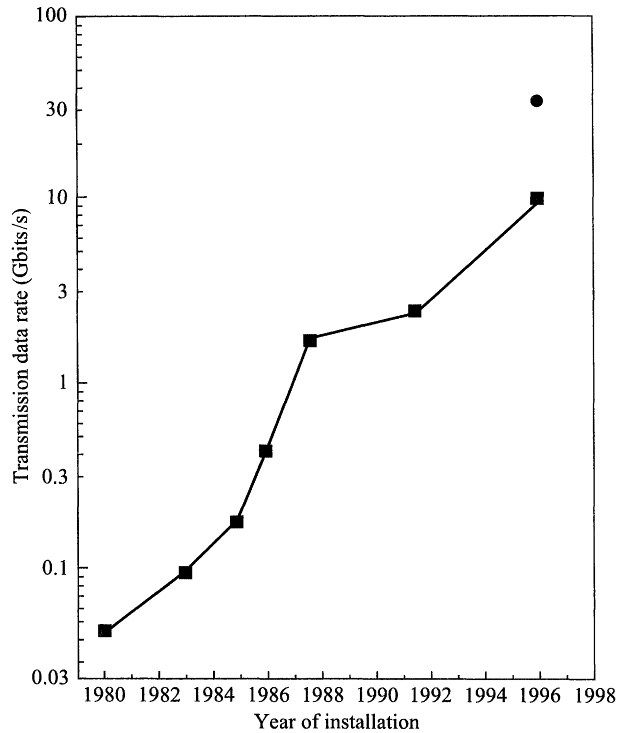


Figure 1.42 Growth of transmission capacity of commercial optical fiber telephone cables: ■, time division multiplexing (TDM) systems; ●, wave division multiplexing (WDM) systems (after [89]).

introduction of lower attenuation graded-index multimode silica fiber and single-mode silica fiber cables. The present single-mode optical fiber cables, which dominate the long-haul telephone cable field, operate at 1.3 μm and are characterized by attenuation values in the range of 0.3–0.4 dB/km. Since their pulse broadening due to material and waveguide dispersion at 1.3 μm is virtually equal to zero, their transmission capacity is still attenuation limited and repeaters must be employed approximately every 40 km. These systems, depending upon their length, can achieve transmission capacities of the order of 1 Gbit/s. It is interesting to observe that the capacity of the much longer transatlantic optical fiber cable, which also operates at 1.31 μm with a repeater separation of 70 km, is 280 Mbit/s per fiber pair (cf. Chapter 17). Nondispersion shifted single-mode fibers, which operate at a wavelength of 1.55 μm at which the reduced attenuation of the fiber is between 0.1 and 0.2 dB/km, may achieve data rates of 10 Gbits/s albeit at reduced repeater spacings. Since the chromatic (material and waveguide) dispersion at 1.55 μm is now finite and of the order of 18 ps/km-nm, the separation of the optoelectronic regenerative repeaters becomes, in addition to attenuation, also pulse dispersion or broadening limited at the wavelength of 1.55 μm. If the single-mode fibers are of the dispersion shifted-type (i.e., the chromatic dispersion at 1.55 μm is reduced nearly to zero), then the dispersion limitation becomes less stringent. Figure 1.43 compares the dispersion-shifted (index profiled) and the regular single-mode fibers, which are operated at wavelengths of 2 and 10 nm below 1.55 μm

[111–113]. It can be readily perceived from Fig. 1.43 that the transmission capacity per channel is greatly augmented in dispersion-shifted single-mode fibers, with further improvements affected the more proximate the fiber is operated to the dispersion-shifted wavelength of 1.55 μm. It is interesting to note that the 9000-km transpacific telephone cable installed in 1991, which operates at 1.55 μm, has a transmission capacity of 560 Mbits/s per fiber pair with repeaters placed at 110–120 km apart, which represents a substantial improvement over the transatlantic cable.

With the advent of erbium doped optical fiber amplifiers in the late 1980s [114–116], which operate in the wavelength region of 1.53–1.56 μm, large increases in the data rate transmission capacity of optical fibers are anticipated. The advantage of the optical amplifiers is that they can amplify simultaneously a large number of wavelengths in a wavelength division multiplexed system [116]. More detailed discussions on optical amplifiers are presented in Chapters 15 and 17, but a few cursory comments are in order here. The erbium-doped silica fiber amplifier essentially consists of a short length of monomode silica fiber (e.g. ~40 ft) in which the erbium ions are raised to a higher level by absorption of the light quanta from a powerful solid-state pump laser operating either at 0.98 or 1.40 μm. When a transmitted optical signal of wavelength 1.55 μm reaches the metastable erbium ions, the erbium ions when stimulated by a signal photon within the wavelength range of 1.53–1.56 μm fall to the ground state, emitting a coherent photon of identical wavelength, phase, and direction as that of the incident ray's photon, thus leading to amplification of the signal [89, 116]. A simplified schematic diagram of the erbium-doped fiber amplifier is depicted in Fig. 1.44 [111, 116]. The pump-signal multiplexer forms a low-loss wavelength selective coupler where from the pump light and signal light are introduced into the erbium-doped silica fiber. The purpose of the optical isolators is to prevent the occurrence of oscillations in the erbium-doped optical fiber amplifier in the presence of reflections. Although the erbium-doped silica amplifiers were developed in 1987, it was only in 1992 that the feasibility of transmitting a 5-Gbit/s channel over a distance of 9000 km without any optoelectronic signal regeneration along the line was demonstrated [89]. A problem, intrinsic to optical amplifiers, is that the transmitted signals are inevitably amplified along with all the incident noise by each successive optical amplifier inserted along the

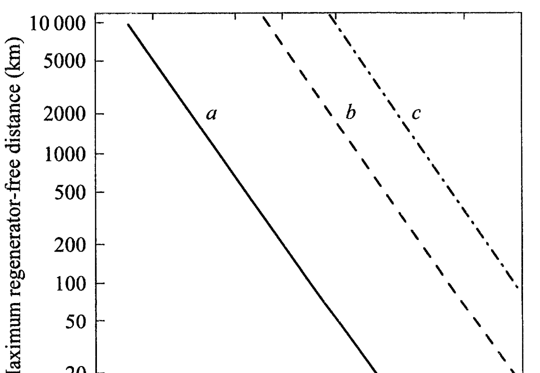


Figure 1.43 Chromatic dispersion-imposed maximum allowable nonregenerative cable distances with their corresponding single channel data rates for single-mode optical fibers: (a) single-mode fiber at the operating wavelength of $\lambda_0 = 1.55\,\mu m$ and dispersion-shifted single-mode fiber operated at (b) ($\lambda_0 - 10$ nm) and (c) ($\lambda_0 - 2$ nm) (after [111–113]).

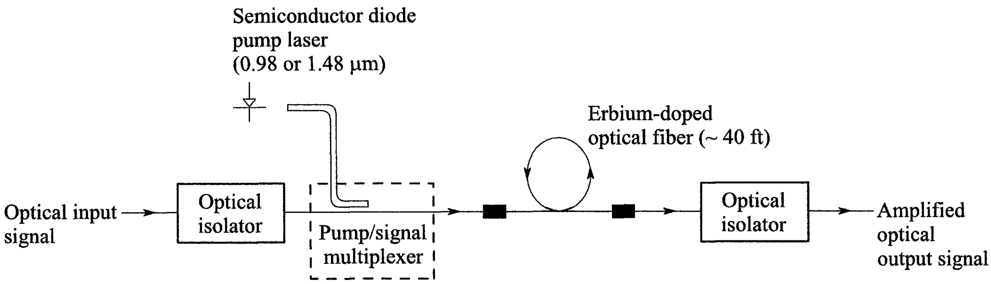


Figure 1.44 Simplified schematic diagram of erbium-doped silica fiber optical amplifier (after [111, 116]).

length of the fiber. In this respect the system behaves somewhat similarly to the wideband analog system used with copper wire cables. Here, however, the noise is generated in each optical amplifier due to spontaneous emission effects; thus each optical amplifier generates its own noise, which in turn is amplified by other optical amplifiers in tandem along the optical fiber lines. It is thus apparent that over a long optical transmission line, in addition to economic considerations, it is equally desirable to limit the number of optical amplifiers in order to mitigate noise accumulation effects.

The design, construction, and manufacturing procedures, which are utilized with optical fiber cables, have benefited greatly from the experiences acquired over more than a century with metallic conductor communication and power cables. The overall rap of the inner portion of the cable or core and the sheath construction of optical fiber telephone cables is either very similar or identical to that employed on metallic conductor telephone cables. The same situation prevails concerning armoring of the optical fiber cables (cf. Chapters 15, 16, and 17). However, in addition, optical fiber cables contain inner strength members of either steel or high-strength polymers for tension reinforcement of the cable. In many respects this approach is analogous to the use of steel-reinforced copper conductors in coaxial cables. As mentioned already, the fibers are further protected from compressive loads by placing them in the form of a bundle or ribbon matrix configurations within loose buffer tubes filled with a gel compound; alternatively, the individual fibers may be incorporated within a tight buffer coating, consisting of an extruded polymer layer. The tight buffered fibers, when stranded, result in a highly flexible cable construction of high strength and crush resistance. However, the typical long-distance multi-optical-fiber terrestrial telephone cables utilize a stranded loose tube (Siemens) or a stranded slotted core (Northern Telecom) or, alternatively, an enlarged central loose tube core (Lightpack cable, AT & T) design (cf. Chapters 15 and 17).

The use of optical fiber cable communication links by power utilities became popular in the late 1970s; this relatively early interest was primarily stimulated because of their immunity to electromagnetic interference. The optical fiber cables, used as communication links between power substations and as inner communication lines of ground wires along overhead power transmission lines, are usually of the four optical fiber core design—two optical fibers for the outgoing signals and two optical fibers for the incoming signals. An example concerns an installation carried out in 1981 at two transmission line substations [117]. In this installation, an ITT-developed optical cable, having the cross section shown in Fig. 1.45, was used to span a total distance of 1.6 km.

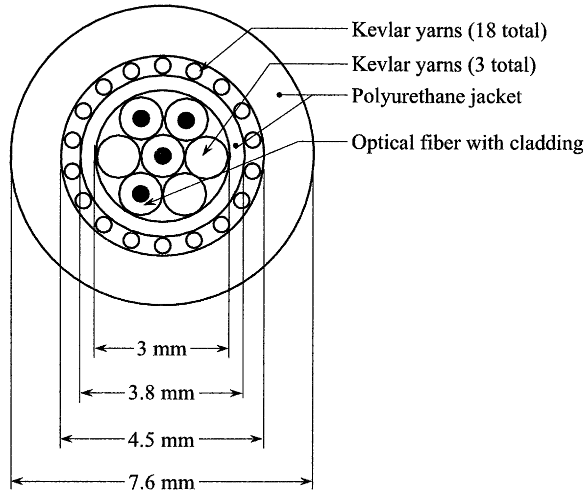


Figure 1.45 Multimode ITT optical fiber cable with protective sheaths [117].

The multimode optical fibers consisted of a doped silica core of 50-μm diameter with an NA of 0.23, enclosed in a borosilicate glass cladding giving a resulting overall diameter of 125 μm. To provide mechanical protection and to reduce microbending effects, a silicone color-coded coating was deployed over the four optical fibers within the cable. Additional mechanical protection was supplied by the use of Kevlar yarns and a double polyurethane jacket. The refractive index of the core was 1.48, and the optical fibers were designed for operation at a wavelength of 0.85 μm; the nominal attenuation of this early optical fiber cable was a relatively high value 6 dB/km.

Another interesting early application of graded-index multimode optical fiber cables occurred as inner communication links housed within bare aerial ground cables that are deployed as a lightning protection on overhead power transmission lines. This design developed by BICC in England is depicted in Fig. 1.46 [118, 119]. The overall

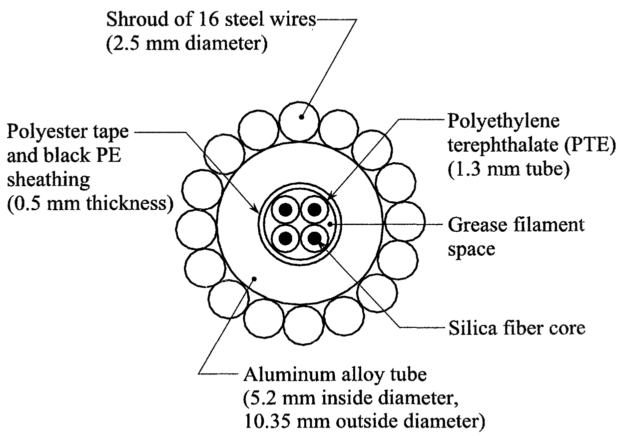


Figure 1.46 BICC optical fiber cable with a ground wire casing [118, 119].

cable shown was installed in 1981 between a substation and a measurement test station over a distance of 2.2 km as an overhead ground wire in a 735-kV transmission line. The lightning protection is attained via the grounded aluminum alloy tube conductor, and the cable support strength is provided by the steel wires. Thus the concentrically disposed optical fiber wires are completely protected from lightning. The cable is characterized by an attenuation value of approximately 2.7–3.7 dB/km for each of the four color-coded optical fiber conductors [118]; it was intended for operation at wavelengths between 0.80 and 0.90 μm [119].

In relation to LANs, we have seen from the previous discussions that twisted-wire pair cables can cost effectively support data rates as high as 100 Mbits/s; however, this can be accomplished only over relatively short lengths. When the required cable lengths are large, then the implementation of optical fiber cables becomes a necessity. For example, optical fiber cables may be used to connect copper-conductor-based LANs between buildings on a university campus or between different office sites of corporations in large cities. If the interconnecting distances are less than 10 km, then the lower cost graded-index multimode fiber cables are the medium of choice. Figure 1.47 portrays for illustrative purposes a typical multimode six-fiber cable that is commonly employed for indoor LAN applications to provide a high data transmission medium between mainframes and building distribution systems. The fibers have a standard 62.5-μm core diameter with 125 μm cladding covered by a coating of 900 μm outside diameter. The multimode fiber has an NA of 0.275; its bandwidth is, respectively, 160 and 500 MHz-km at the transmission wavelengths of 0.85 and 1.30 μm; the corresponding maximum attenuation values are 3.4 and 1.0 dB/km, respectively. The permissible minimum bend radii are 270 mm during installation and 180 mm over the long-term service conditions. It should be observed here that following recent standardization, most multimode fibers are currently manufactured with 62.5 μm core diameters in lieu of the 50-μm core diameters that characterized the earlier multimode optical fiber

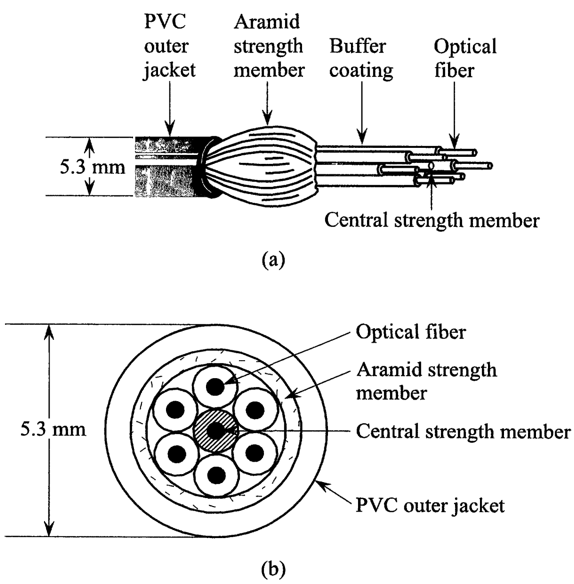


Figure 1.47 A 62.5-μm core six-fiber graded-index multimode optical fiber cable for indoor LAN connections between mainframes and building distribution systems: (a) profile view; (b) cross-sectional view. (Courtesy of Belden Wire and Cable Company.)

telephone cables. However, very recently, the 50-μm core multimode fiber has received increased attention, because its smaller value of NA vis-à-vis that of the 62.5-μm core fiber provides a greater transmission bandwidth [120, 121]. In addition the 50-μm core multimode fiber functions very well in conjunction with the recently developed vertical-cavity surface-emitting laser (VCSEL) at the wavelength of 0.85 μm.

Comparative bandwidth and corresponding maximum fiber cable length test data on 50 and 62.5-μm core multimode fibers has been recently compiled by the IEEE 802.3z Committee, concerning the backbone fiber interconnection of the newly planned Gigabit Ethernet Standard [121]. The results are presented in Table 1.14; it can be perceived that although at 1.3 μm both the 50- and 62.5-μm core multimode fibers have approximately equal bandwidths and maximum allowable interconnection fiber lengths, the 50-μm core multimode fiber is characterized at 0.85 μm by a larger bandwidth and, consequently, by a greater permissible maximum backbone link distance.

Since single-mode fiber cables with the associated laser or semiconductor diode light sources are more expensive, they are used in local area network applications only when greater data transmission rates and longer distances are involved. Figure 1.48 depicts a monomode optical fiber interbuilding cable containing six loose-type buffer tubes filled with a gel compound; there are six monomode fibers per tube. The cable is fully armored with a PE jacket and is suitable for direct burial; it is typically used to interconnect LAN networks for wide area network (WAN) applications. The buffer tubes are 2.5 mm in diameter, and the monomode fibers contained therein have respective nominal attenuation values of 0.45 and 0.35 dB at 1.31 and 1.55 μm, respectively; their corresponding maximum pulse dispersion values at the same wavelengths are, respectively, 2.8 and 18 ps/km-nm.

A local area network, which is specifically designed for optical fiber cables as the connecting media, is the FDDI (fiber-distributed data interface). It is essentially a high-speed Token Ring network defined by the American National Standards Institute in ANSI Standard X3T9.5, which specifies a ring with a data rate capacity of 100 Mbits/s that can support a maximum of 500 nodes or workstations with a separation of ≤ 2 km between the nodes [92, 122]. As in the Token Ring network, the workstations are connected in the form of a ring, but the connections are made with optical fibers, i.e., each station has an input fiber from the preceding station and an output fiber to the station in tandem. The FDDI loop contains in addition a secondary fiber in parallel with the primary fiber, whose purpose is that of a spare in the event that failure should occur in the primary fiber. In such circumstances, the primary and secondary fibers are joined to reconstitute the ring. The physical length of the ring itself may extend up to 200 km.

TABLE 1.14 Gigabit Ethernet Multimode Optical Fiber Bandwidth and Maximum Backbone Link Distance as a Function of Wavelength

	Modal Bandwidth (MHz-km)		Backbone Link Distance (m)	
Fiber Core Size (μm)	0.85 μm	1.30 μm	0.85 μm	1.30 μm
62.5	160	500	220	550
62.5	200	500	275	550
50	400	400	500	550
50	500	500	550	550

Source: From IEEE 802.3z Committee [121].

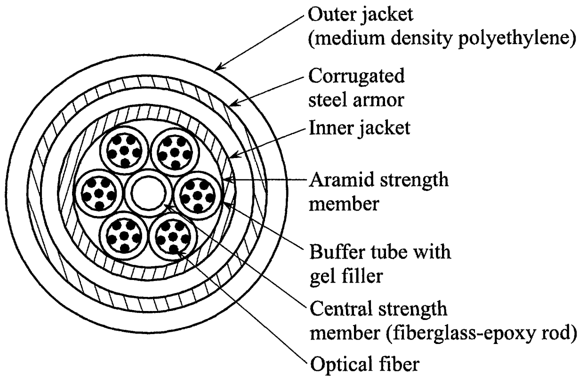


Figure 1.48 A 36-monomode optical fiber interbuilding trunk cable. (Courtesy of Belden Wire and Cable Company.)

Figure 1.49 delineates the topology of the FDDI network dual ring [92, 122]. The dual-attach station in the FDDI network dual ring is essentially a connection concentrator, which performs the function of the media or multistation access unit (MAU) in the Token Ring LAN network (cf. Fig. 1.31). It has two inputs and two outputs for the optical fiber cables, in contrast to the single input-output attach workstations, which are connected via the concentrators to the dual fiber ring. When the workstations are unactivated, they are bypassed by the concentrator. The dual-attach station remains always activated, since one of its prime purposes is to monitor continuously the performance of the optical fiber cables; should a fault be sensed in the primary optical fiber by the dual-attach station, the secondary fiber would be immediately placed into operation.

All single-attach stations comprising the ring have their inputs and outputs directly connected to a concentrator, which automatically maintains continuity of the ring path

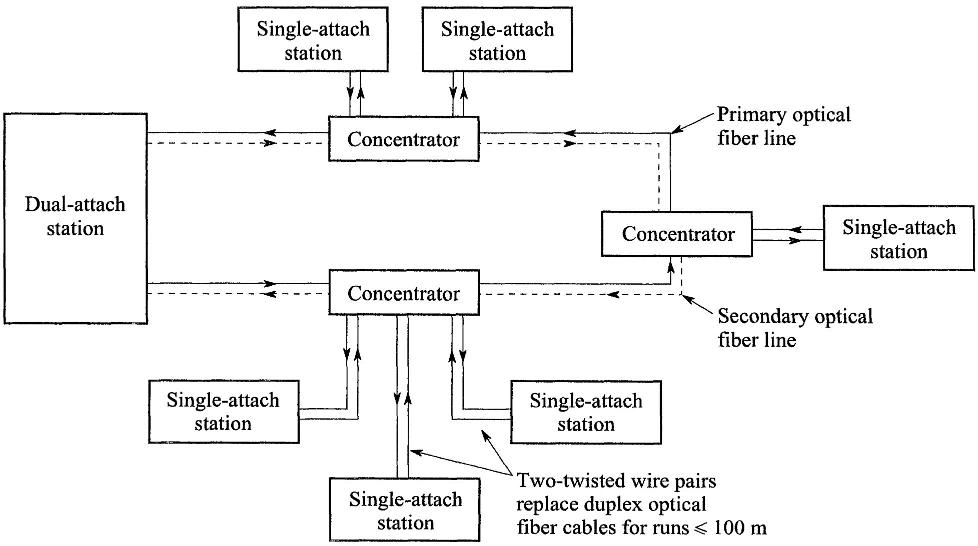


Figure 1.49 Simplified schematic of 100-Mbit/s dual-optical-fiber FDDI ring network (after [92, 122]).

irrespective of whether the machine is removed or turned off. Note that if the distance between the concentrator and a given single-attach station is less than 100 m, a lower cost two-twisted-copper-wire pair cable may be utilized in lieu of the duplex optical fiber cable. Adaptive circuitry would then form part of the concentrators, which would remain interconnected with the dual fiber backbone cable of the high-capacity FDDI long-distance ring. The concentrators also act as repeaters along the optical fiber ring over which data frames are transmitted in the form of a serial stream of bytes [92, 122]. The data is always transmitted in the same downstream direction, i.e., each station repeats the symbol stream, which it receives from an adjacent upstream station, and transmits it to its adjacent downstream station until the data frame reaches the station of origin and is removed from circulation. A new data frame is then initiated by the next station in possession of the token (digital code word) as in the case of the IBM Token Ring network.

Transmission along the FDDI dual ring is synchronized; accordingly, each node/workstation must synchronize its local clock to the received symbol stream from adjacent upstream node/workstation and decode the data. Thus, when transmitting the symbol stream to the adjacent downstream node/workstation, the node/workstation must combine its local clock signal with the data. The data in the FDDI dual ring is transmitted in the form of symbols, using an encoding process whereby four bits of data are transmitted along the fiber as a 5-bit symbol (e.g. 11160, 01001, etc.) corresponding to a cable data rate of 100 Mbits/s [92, 96]. The encoder employs a non-return-to-zero, invert on ones ((NRZI) waveform, whereby a 1 causes the LED source at the input of the optical fiber to switch states, that is from off to on or vice versa; while a 0 instructs the light-emitting source to remain fixed at its given state (on or off). However, the number of 0s in succession is limited to three in each of the five-bit symbols in order to limit the duration of the fixed-state period. The encoding/decoding procedure is illustrated schematically in Fig. 1.50; the flat cable shown is extensively employed in computer networks wherever parallel wire port connections are involved.

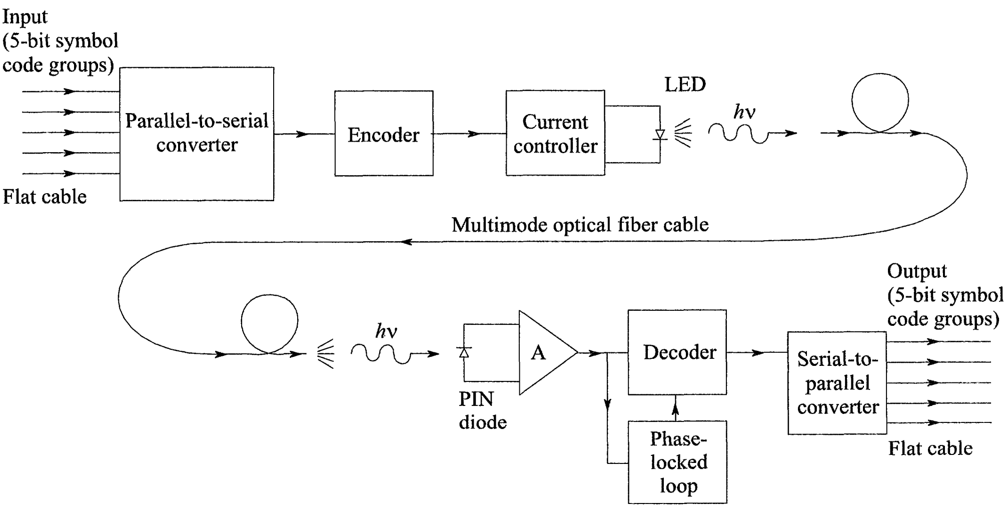


Figure 1.50 Schematic diagram of transmitter and receiver at two nodes of the FDDI network (after [92]).

The ANSI Standard X3T9.5 on the FDDI network specifies 62.5-μm core multimode fibers for distances ≤2 km and single-mode fibers for interconnection distances up to 60 km in length. A multimode duplex optical fiber cable depicted in Fig. 1.51 is suitable for short-distance applications; it is characterized by an NA value of 0.275 and has a core diameter of 62.5 μm with cladding and buffer diameters of 126 and 900 μm, respectively. It is designed for operation at wavelengths of 0.85 and 1.30 μm with corresponding maximum signal attenuation values of 3.4 and 1.0 dB/km respectively; its corresponding bandwidths at the same wavelengths are 160 and 500 MHz-km, respectively (cf. Table 1.14) It is intended for indoor LAN applications, but may be used also for outdoor installations when protection is provided in the form of ducts or conduits. When used as a cable between the concentrator and a single-attach station in the FDDI network, one fiber is employed for transmission and the other for the reception of data. For connections forming the actual dual ring in the FDDI network between the concentrators and the dual-attach station, one fiber acts as the primary fiber with the other fiber as the secondary or standby fiber (cf. Fig. 1.49). The optical fiber interconnections are made by means of a fixed shroud duplex (FSD) connector, which provides protection for the two signal transmitting and receiving fibers that are recessed within a shroud [92]. For long cable lengths dispersion-shifted monomode optical fiber is substituted for the multimode fiber, though the overall dual-fiber cable construction delineated in Fig. 1.51 remains essentially unaltered. Typical dimensions of the monomode silica fiber core, its cladding, and protective coatings are given in Fig. 1.52. At the transmission wavelengths of 1.31 and 1.55 μm, the single-mode fiber is characterized by attenuation values of 0.5 and 0.4 dB/km, respectively; the corresponding maximum chromatic dispersion values are 2.8 and 18 ps/km-nm, respectively.

In concluding our survey on communication cables, some general observations are in order, because over the last several decades the telecommunications transmission medium has undergone profound change. The changes were motivated by attempts to improve the quality of voice and video transmission and to accommodate increased

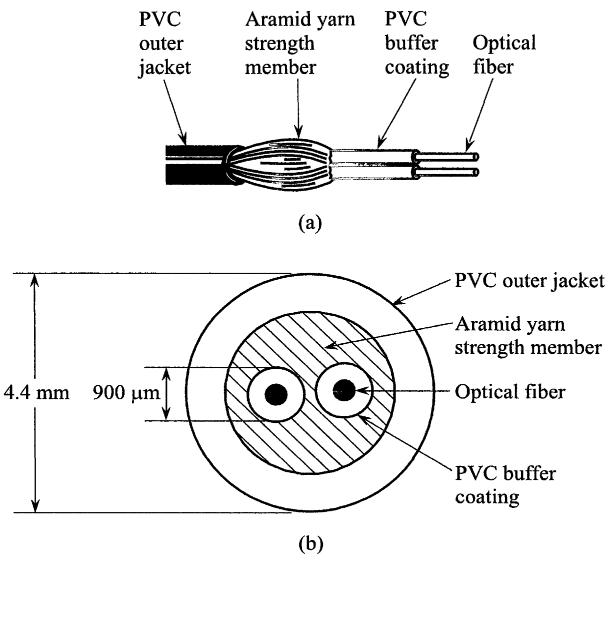


Figure 1.51 Duplex 62.5-μm core multimode optical fiber for use as a short-distance transmission medium in FDDI dual-fiber networks: (a) profile view; (b) cross-sectional view. (Courtesy of Belden Wire and Cable Company.)

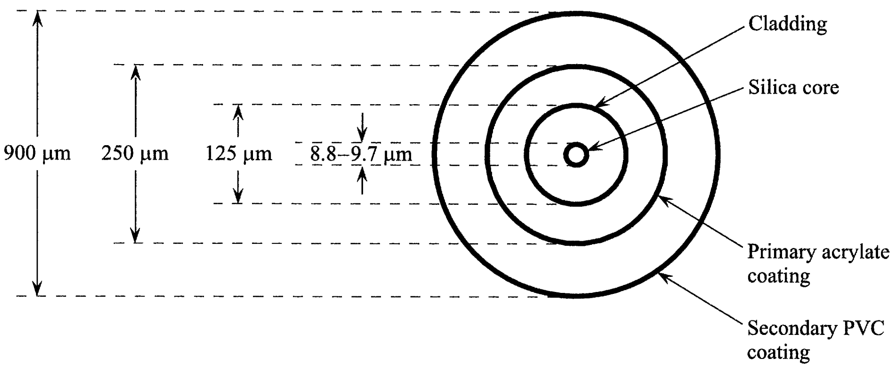


Figure 1.52 Dimensions of a monomode silica fiber with cladding and protective coatings. (Courtesy of Belden Wire and Cable Company.)

data transmission rates through digital transmission techniques and improved low-loss, wide-bandwidth cables. Long-distance communication and data transmission benefited greatly from the introduction of very low loss optical fiber cables, which rapidly displaced the metallic conductor cables used in long-distance transmission applications. However, the ever tenaciously cost-effective metallic conductor cables continue to be used for short-distance applications in local area networks and over a very substantial portion of the cable distribution network in the local telephone subscribers loop. The metallic cables in the local loop represent an enormous investment and various electronic techniques have been developed to enhance the signal transmission capacity of these in situ cables to meet the increased data requirements of the telephone subscribers' computer networks.

In 1984, the International Telegraph and Telephone Consultative Committee (CCITT) began work to establish standards for an integrated systems digital network (ISDN), which is to provide end-to-end digital connection over the existing telephone transmission and distribution network for voice and nonvoice services to which users may have access via standard multipurpose network interfaces. This will permit LANs to communicate directly over the telephone transmission system. Evidently, at present, the subscriber loop is an analog system and the digital signals from the subscribers' PCs must be transformed by means of a modem into analog signals for transmission over the local loop telephone cable network. The implementation of digital services in accordance with the ISDN plan is bound to bring the fiber cables closer to the telephone subscribers' premises. However, to exactly what degree this will affect the use of the traditional twisted-wire pair telephone cables in the subscriber loop is difficult to predict. The twisted-wire cable has proven to be very resilient, particularly for signal transmission over short distances. For those of us who were associated with the telecommunication industry in the 1950s, it may be recalled that in that epoch few would have conjectured that the twisted-wire pair cable, which was originally intended only for voice frequencies, would be tested at 600 MHz and be deployed for data transmission rates of 100 Mbits/s and, furthermore, in conjunction with data compression techniques for the transmission of high-quality video signals.

As local area networks proliferate, the demand for both traditional copper cable and optical fiber cable continues to increase. Most of these networks are copper wire based, though an increasing number are beginning to employ optical fiber cables for the network backbone and long-distance interconnections. Yet even in the all-fiber FDDI networks there is a place for copper cables involving short runs to the individual workstations, because of the inherently lower expenses associated both as concerns the metallic cables themselves and their installation. In the present highly competitive environment, short-run installations tend to favor metallic conductor communication cables. Replacement of copper conductor cables with optical fiber cables will obviously not enhance the bit rate capacity of the LAN network itself, though the optical cables will augment the immunity of the network to extraneous electrical interference and obviate data security concerns by eliminating signal radiation.

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