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Estimated Cost of a Submarine Fiber Cable System

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ABSTRACT

This report is based on published cost figures of the TAT-6 submarine coaxial cable system which went into service on July 27, 1976. Assuming readiness of long wavelength (1300 nm) devices by the late 1980's, we project the expected cost of a fiber cable system based on the TAT-6 experience. The study shows an expected normalized cost savings (dollar per channel kilometer) of 37 to 52 percent, in constant dollars.

Key Words: economy; fiber cost; guided waves, optical fibers; submarine cable systems

1. INTRODUCTION

Transatlantic communication demands have grown at a rate of twice the domestic rate for more than 20 years. The growth is currently between 20% and 25% per year. A 20% annual growth causes the traffic to double in less than 4 years. Table 1 shows the growth in the capacity of transatlantic cable systems in 20 years, as well as the projected requirements for 1985 and 1990, based on a 22% annual growth rate.

Because of the high quality of submarine cable circuits and the ease and convenience of International Direct Dialing (IDD), which is becoming commonplace, the continued rapid growth in demand will likely continue. The cost of underwater cable systems, relative to satellite links, depends on traffic and density. Cables have an advantage over short paths, especially if traffic is heavy. As distance increases and/or density decreases, satellites become economically more attractive. The U.S.-Europe traffic is very heavy and can be met with point-to-point links such as cable circuits. Cables have an advantage over satellites in delay time. Cable signal delay is about 65 milliseconds for the transatlantic route, which is not objectionable to most voice traffic users. Satellite echo delays are typically eight times longer (about 1/2 s.), causing frustration to the untrained user. About 10 percent of the users find the cable delay time unacceptable while nearly 20 percent find satellite delay times unacceptable. From this standpoint, then, cable systems have an advantage.

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TABLE 1. Transatlantic Cable Systems**

Year	Total Voice Circuits (Cummulative)	Voice Circuit Added	System Nomenclature (added system)	Cable Size (cm)	Repeater Spacing (km)
1956	36	36	TAT-1	1.57	70.5
1959	72	36	TAT-2	1.57	70.5
1963	212	140	TAT-3	2.54	37.1
1965	352	140	TAT-4	2.54	37.1
1970	1172	820	TAT-5	3.81[1]	18.6
1976	5372	4200	TAT-6	4.32[1]	9.5
1985	32165***	26790***			
1990	86930***	81558***			

** Source: O'Rorke (1980).

*** Estimated, based on 22% annual growth.

[1]These reported values (from O'Rorke, 1980) are the inside diameter of the outer copper conductor. Outside cable diameter is 4.45 cm for TAT-5 and 5.26 cm for TAT-6. The outside diameter is the dimension of interest in later calculations.

The introduction of satellite service between the United States and Europe has had a delaying effect on cable demand but the growth trend continues. The recent trend is to divide traffic about evenly between satellite and cable circuits. If the annual growth rate is 22% (for example), the demand doubles in about 3-1/2 years. Satellite service has the effect of shifting the demand curve by about 3-1/2 years, but the slope remains unchanged.

This report concentrates on cable systems. Satellites have certain advantages (and disadvantages) but a discussion of these matters is beyond the scope of this report. Past trends do not reflect the new need for mixtures of voice, video, and data. A mixture of such messages is handled most easily on all digital systems. Fiber waveguides are relatively more hospitable to digital signals than coaxial cables. There are some (Kirkland and McDonald, 1979; Dawidziuk and Williamson, 1979) who suggest that analog transmission on coaxial cables has reached a practical maximum. Repeater spacing for the TAT-6 is about 9.5 km and the cable is 5.26 cm in diameter. Increasing the cable size further and/or reducing the repeater spacing becomes economically unattractive. Furthermore, as pressure for digital systems continues, the coaxial cable becomes less attractive since it is not well suited for digital signals.

The trend seen in Table 1 is clear: ever increasing cable size is required to accommodate ever increasing traffic demands. This is a basic characteristic of metallic transmission lines. Optical fiber waveguides offer a striking contrast in this regard: the size of the optical fiber has little influence on its capacity. Indeed, the single mode fiber must be small (to maintain its monomode character) but offers the greatest communication capacity. In general, fiber capacity is not influenced by its size, except in a secondary way. Decreasing fiber size frequently leads to an increase in communication capacity.

Major costs and the total cost of the TAT series of transatlantic cables are listed in Table 2. Certain trends are evident, but the economy of the day apparently was also instrumental in determining cost.

TABLE 2. Cost of Transatlantic Cable Systems*

Designator	Total Cost ($ M)	Percent of Total Cost: Cable	Installation	Submerged Electronics	Cable Size (cm)	Repeater Spacing (km)
TAT-1	49.58	50.2	2.4	17.9	1.57	70.5
TAT-2	42.7	60.9	4.5	14.1	1.57	70.5
TAT-3	50.6	57.5	4.0	24.5	2.54	37.1
TAT-4	50.4	59.2	4.0	24.8	2.54	37.1
TAT-5	79	50.1	4.3	33.2	3.81	18.6
TAT-6	197	52.3	5.1	39.6	4.32	9.5

* Source: O'Rorke, 1980.

The cost of installation would normally be a strong function of cable size, but some contrasts are seen in the table (cable size and repeater spacing are repeated in Table 2 for easy reference). For the most recent system (TAT-6) with repeater spacing of 9.5 km, the cost of submerged electronics is about

40% of the total cost, nearly equal to the fractional cost of the cable. If repeater spacing could be doubled, the impact on system cost would be substantial. The fiber system discussed later offers a tripling of repeater spacing but with an associated increase in cost per repeater unit.

The large cable laying ships can carry over 400,000 ft^3 of cable. In practice, because of the weight of modern cables, they freqently carry only about half the rated volume. The cable ship CABLE VENTURE (formerly the NEPTUN), for example, has volume enough to carry 444,000 ft^3 of cable but carries only about 222,000 ft^3 because of the weight factor (Peirce, et al., 1969).

In this report, we take the recent TAT-6 system as a basis of the expected cost of a fiber system covering the same route, using constant dollars, assuming the use of 1300 nm optical devices and low-loss monomode fibers. The cost of the TAT-6 system is now a matter of record and this forms the basis for the cost of a well-designed fiber cable system. Since the fiber system is a matter of speculation, we can only estimate the various cost entities, but the TAT-6 system forms a convenient basis for those estimates. The fiber cable is assumed to contain six fibers, each of which carries the traffic now carried by the TAT-6 system.

At this writing, the TAT-7 system is not yet in place so cost figures are not available. A new cost comparison based on TAT-7 costs would be desirable.

2. FIBER WAVEGUIDE SYSTEMS

Recent developments in the technology of optical waveguide communications suggest that high quality monomode fibers, laser diode sources, and low-noise detectors will provide reliable and economical service for voice, video, and data, utilizing a digital signal format which allows a mix of the three message types. Optical fibers are much lighter and smaller than coaxial cables; that will influence the cost of laying the cable. Fibers are much more hospitable to digital signals than their metallic cable counterparts; this is important in the trend to digital transmission and the mixture of video, data, and voice signals. Fiber systems also promise repeater spacings considerably greater than that of coaxial systems.

The projected lifetime of optical components is still a matter of speculation. Accelerated life tests are encouraging but not definitive. Redundancy will probably be called for, adding expense and complexity to the sytem. The advantage of such redundancy clearly outweighs the disadvantages, however.

Long-haul fiber systems show promise of economy at wavelengths of 1300 nm and 1500 nm. Sources and detectors at these wavelengths are not yet well understood, however, and therein lies the weakness of fiber systems. Based on realistic projections from reputable laboratories around the world, however, this snag will be eliminated in the next 4 or 5 years. The sources and detectors will, by then, be reliable, fast, and relatively inexpensive. Because of the economic gains associated with the advantages listed above, submarine fiber systems will undoubtedly be viable in the late 1980's.

In this section we will give technical projections on fiber system capabilities and the impact of such projections on economic viability.

2.1 Sources and Detectors

The light sources of interest in optical waveguide communications fall into two distinct groups: those that operate at 800 to 900 nm wavelengths and those for use at 1100 to 1700 nm wavelengths. The first group is technologically more mature than the second. The AlGaAs devices (800 to 900 nm) are well understood by now and have respectable lifetime projections. They are reliable, fast, and relatively inexpensive. The detectors available at the shorter wavelengths are well established, being based on silicon technology, which is one of the better understood technologies. The quantum efficiency of silicon (Si) photodetectors is about 85% at the wavelength of interest and they are fast enough to accommodate 1 Gbit/s rates (about 15000 voice circuits). The dark current of Si detectors is sufficiently low to preclude system degradation on that account. In short, the technology of sources and detectors in the 850 nm range is mature, field tested, and reliable.

The solid technological base of 850 nm devices notwithstanding, there is a pressing need to turn to the longer wavelengths for the high-bit-rate, long-haul systems. The reason is two fold. First, the fiber has low attenuation windows at 1300 nm and 1550 nm, and second, the dispersive property of fibers (especially single-mode fibers) shows a marked improvement at the longer wavelengths. More will be said of this when discussing the fiber waveguide. Suffice it for now to state that, for the single-mode fiber operating at the optimum wavelength around 1300 nm, a system would usually be attenuation limited, meaning that repeater spacing on the order of 30 km or more would be possible.

For the 274 Mb/s system under consideration, we assume the power out of a laser diode is +3 dBm (Anderson, et al., 1980); taking coupling loss as 5 dB yields -2 dBm into the fiber. The values quoted here and in the preceding paragraph will be used in a subsequent calculation of expected repeater spacing.

A submarine cable system will require a life expectancy of 24 years with about 8 years mean time to failure. Redundancy will be required in the repeater section to insure such reliability. Current plans call for as many as four laser diodes in a redundancy configuration for each repeater. The associated switching circuitry introduces additional loss and supervisory signalling from shore but the result is a less stringent reliability figure for the laser diode. The insertion loss of the switch is expected to be less than 2 dB (Runge, 1980).

2.2 Fiber Connectors and Splices

It was once thought that splicing and coupling presented major obstacles to the practical implementation of single-mode fibers. The successful use of a fusion technique, however, was instrumental in removing this basic fear. The suface tension which is inherent in the technique provides a self-alignment process which precedes the weld, yielding consistently low-loss splices. Losses of 0.2 dB can be expected as a matter of course, even for single-mode fibers (Hatakeyama and Tsuchiya, 1978).

Demountable connectors are important to repeater design. A system may call for only a few connect-disconnect cycles, but those connections must be reliable and repeatable. Low loss requires precise axial alignment and durability. Precision metal plugs using V-grooves are frequently used but triangulation of various sorts have been tried with success. The alignment problem is more critical for small core sizes so single mode fibers have severe connector tolerances. In spite of such stringent requirements, the loss of demountable connectors is expected to be 0.5 dB or less, with reliable consistency (Kimura, 1980). Refinements on the basic mechnical alignment technique may evolve in the next few years, but no dramatic improvements are expected.

A compound lens connector shows promise as a novel approach to a demountable configuration (Holzman, 1978) but losses remain in the 0.5-dB range, even for a multimode fiber. The lensed configuration is not available for single-mode fibers. In later calculations, demountable connector loss of 0.5-dB will be assumed; this value is based on recent published values (Kimura, 1980; Dalgleish, 1980).

As stated earlier, there are still impediments to long wavelength operation. The sources and detectors are not yet as mature (technologically) as the 850 mm devices, and this causes some concern to undersea cable system planners. However, the technology of such devices is developing at a significant pace; long wavelength systems installed in the late 1980's or the early 1990's will use components that are as reliable as the current 850 nm components.

The choice between the 1300 nm regime and the 1550 nm regime is complex. A basic attenuation mechanism (Rayleigh scattering) causes loss that decreases as λ^{-4}. On the basis of this alone, then, 1550 nm is more desirable than 1300 nm operation. The trend in optical sources, however, definitely favors 1300 nm. Thus, components for systems of the mid- to late-1990's will likely be the 1550 nm ones; for this study (the late 1980's) we will assume 1300 nm operation. Components in that wavelength regime are more advanced and more likely to be ready in the time frame of interest here. Fiber attenuation at 1500 nm is about 0.2 dB/km less than at 1300 nm. In the remainder of this study, 1300 nm operation will be assumed.

At 274 Mb/s (equivalent to about 4200 voice circuits, corresponding to the TAT-6 coaxial cable system), the sensitivity of a simple InGaAs p-i-n photodiode with a GaAs FET transimpedance front-end amplifier is about -36 dBm (measured) (Lee, et al., 1980). About 3 to 6 dB can be gained from an avalanche photodiode (APD) (Ogawa and Chinnock, 1979). For the long wavelength regime APD's do not yet have sufficient reliability to warrant use in submarine systems, where reliability is critically important. In addition, the APD requires a high-voltage bias supply and temperature stabilizing circuitry which must meet reliability constraints. Thus, the 3 to 6 dB gain is not sufficient to warrant use of the APD: the p-i-n detector is preferred. Sensitivity as low as -38.9 dBm has been reported for such photodetectors (Smith, et al., 1980) but for the calculations that follow, we will use the sensitivity value of -36 dBm to establish likely repeater spacing. That value is consistent with estimates of what can realistically be expected in modern and future systems (Kimura, T., 1979: 1980).

The power coupled into a single mode fiber can be improved by shaping the end of the fiber to form a lens. Without such coupling aids, about -8.5 to -8.2 dBm has been coupled from a laser diode into a single mode fiber (Yamada, et al., 1979). Forming the fiber end to improve coupling has reduced coupling loss to 3 to 5 dB for a single mode fiber (Kuwahara, et al., 1980; Kimura and Kanbe, 1980).

2.3 Fiber Waveguide and Cable

The selection of an optical fiber waveguide has profound implications on the cost and capability of a submarine transatlantic system. The cable cost is certain to be the major contributor to component cost. This was the case for coaxial systems (Table 2) and will likely not change for fiber systems, although the absolute value of that cost will probably change. A properly chosen fiber waveguide has immense circuit capability, especially in comparison to the coaxial cable counterpart. Engineering economy then demands that the fiber capability be fully exploited to reduce cost per circuit kilometer.

The limitation of a fiber waveguide system is due to one of three causes:

1. Speed of terminal components.
2. Pulse disperson introduced by the fiber.
3. Low signal level at the detector (i.e., high fiber attenuation).

These will be discussed in the following three sections.

2.3.1 Utilization of terminal components

The speed of optical components (sources and detectors) is adequate for most systems being contemplated. Laser diodes available today are capable of handling 274 Mb/s (which is the rate under consideration for this study) without trouble. The use of a sophisticated multiplexing scheme is envisioned when 274 Mb/s grossly underutilizes the fiber waveguide, but a single laser source and the associated detector are, even now, fast enough to accommodate the data rates of interest.

In future systems, the bit rate capabilities of a submarine cable link may be improved by utilizing wavelength division multiplexing (WDM) at the expense of a few dB insertion loss (Miki and Ishio, 1978; Ishikawa, et al., 1980). WDM can be utilized in either of two ways. First, the downstream and the upstream signals are on the same fiber but at different wavelengths. This avoids the use of a separate fiber for each transmission direction. It requires a demultiplexer at each end of the link but the expense of a separate fiber for each direction is avoided. The second technique uses one fiber for upstream signals and another for downstream signals. In this case, several sources and a multiplexer, as well as a demultiplexer and several detectors, are at each end. Regenerators and repeaters become more complicated and more expensive, as expected, but there is almost certainly a net savings on a per-channel-kilometer basis because of the number of channels that can ultimately be accommodated by each fiber. Unfortunately, the state of the art for optical filters is not sufficiently advanced to allow firm plans for WDM on submarine cable systems. Diffraction grating filters allow a large number of channels to be demultiplexed but insertion loss is about 4 dB. The filters are easily mass produced with low material cost. However, the technology is still in its infancy.

Wavelength division multiplexing becomes more attractive as absorption windows of the fiber are reduced, yielding a relatively flat loss curve across a broad range of source wavelengths. This broad. low-loss region of a fiber now appears possible due to recent developments in reducing OH radical content (Moriyama, et al., 1980; Stone and Burrus, 1980).

2.3.2 Fiber attenuation

The reduction of signal amplitude is attributable to several factors, including fiber material properties, geometric nonuniformities, joint defects, and modal properties. The material properties of interest include material absorption and Rayleigh scattering. The latter describes the scattering of optical energy by particles that are small (less than about 1/10 of the light wavelength) and whose refactive index is near that of the surrounding medium. The optical fiber contains randomly dispersed particles and associated Rayleigh scattering, which causes the intensity of scattered light to decrease inversely as the fourth power of wavelength.

Material absorption causes loss from fundamental resonances, absorption trailing edges, and harmonics. The hydroxyl (OH) impurity and transition metal ions are bothersome in the wavelength range of interest and their population must be reduced to only a few parts per billion in some cases. The transmission window of interest in modern silica fibers is from about 800 nm to about 1800 nm. At the lower end of this range, ultraviolet absorption is important; at the upper end, infrared absorption limits the transmission capability. In the window region, total attenuation is 0.5 to 0.8 dB/km, including the effects of geometric nonuniformities, joints, impurity absorption and Rayleigh scattering. Fortunately, the vapor phase axial deposition method of drawing fibers (Izawa and Inagaki, 1980) allows very long lengths of fibers to be drawn, reducing the need for couplings and splices. In Section 2.3.3, we will use a rather liberal value of 1 dB/km for cabled fiber attenuation at 1300 nm, including splices, coupling, and miscellaneous losses.

2.3.3 Fiber Dispersion

The bandwidth of a fiber depends on its structural (geometric) properties and its material characteristics. In general, a fiber provokes signal distortion because of chromatic and intermodal dispersion. Single mode fibers do not suffer intermodal effects and one is left only with chromatic dispersion, caused by propagation delay differences among different spectral components of the signal. The variation of material properties with frequency is a major contributor to chromatic dispersion; this is called material dispersion. Other phenomena, such as intermodal coupling (for the multimode fiber) and polarization effects can also influence signal distortion. Birefringence and strain-induced anisotropy become important in monomode fibers when operating wavelength is chosen to minimize chromatic dispersion.

Materials of interest for low-loss fibers have zero material dispersion near $\lambda = 1300$ nm. This has prompted interest in developing terminal components for use at this wavelength. The bandwidth capability of fibers is high at the point of minimum material dispersion, especially if the refractive index profile is patterned to minimize the intermodal effects or if a monomode fiber is used. Thus, operation near 1300 nm is highly desirable. Actually, the system view of a link introduces nuances that complicate the selection of operating wavelength, as follows.

In the previous section, discussion centered on fiber attenuation. Rayleigh scattering, a fundamental cause of attenuation, decreases as λ^{-4}. There is thus reason to operate at longer wavelengths, to take advantage of this decreasing attenuation with increasing wavelength. Absorption peaks, especially those associated with OH ions, tend to limit desirable wavelengths to certain windows, one of which occurs at 1300 nm and another at about 1550 nm. Because of Rayleigh scattering, 1550 nm is more attractive; the attraction to 1300 nm is based on material properties and signal distortion. This dichotomy is resolved in a system design from operational factors: is the system attenuation limited or disperion limited? What is the time frame of interest? Sources and detectors for use at 1300 nm are more advanced than those at 1550 nm. However, this could easily change in the next few years.

Very recent developments have made wavelength selection easier, especially for a long-haul, high-bit-rate system. Recent analysis predicts, and experiments confirm, that single mode fibers can be structured such that the zero dispersion wavelength can be adjusted to fall anywhere in the 1300 nm to 1600 nm range (Gambling, et al., 1979; Cohen, et al., 1979; and Cohen, et al., 1980). This is accomplished by adjusting the fiber material and parameters such that the negative material dispersion is balanced against the positive waveguide dispersion. Operating wavelength can then be chosen on the basis of attenuation and/or terminal component properties.

The bandwidth of a monomode fiber at the optimum operating wavelength (minimum chromatic disperion) depends strongly on the spectral width of the source. For a source spectral width of a few nanometers (which is readily available from modern laser diodes), the range bandwidth product is well above 300 GHz•km unless core ellipticity introduces birefrigence effects; a 5% core ellipticity, with no offsetting mode mixing, may decrease this bandwidth to about 50 GHz•km, which is more than adequate for long-haul applications. This latter figure means that a 5 GHz signal could be transmitted a distance of 10 km without excessive distortion.

In the calculations of anticipated repeater spacing (below), we will assume that the system is attenuation limited; the power available at the detector, rather than signal distortion, determines repeater spacing. Power launched, receiver sensitivity, splice loss, connector loss, and fiber attenuation will be the system variables that determine economy.

2.3.4 Fiber waveguide cables

The Atlantic ocean bed is an inhospitable environment for a transmission line. The cable must be able to withstand the rigors of laying and retrieving (for occasional repair operations), and the demanding environment of the ocean floor. The signal transmission line is small (typically a few millimeters in diameter) but the armor required for robustness leads to a cable of substantial weight and size. Even so, there is a dramatic advantage in weight and size over the coaxial cable counterpart. The cable design calls for stability during the cabling, transporting, and laying operations. The fiber must withstand severe hydraulic pressure (800 kg/cm^2) and it must be restrained from elongation during the laying operation.

The trend is to place several fibers at the center of the cable to minimize fiber strain during installation, and to provide protection against the forces of water pressure (Anderson, et al., 1980; Nakahara and Uchida, 1980). The steel wire strength member and the copper or aluminum power conductor are the major contributors to cable weight. The fiber cable is much smaller than the coaxial cable in spite of the need for protective armoring. The major advantages of optical cables are its light weight, small size, and large capacity. The attenuation of the fiber allows a significant reduction in the number of repeaters required.

In the following section, we give attention to cost advantages of submarine fiber systems over coaxial cable systems. In preparation for that discussion, here follows a comparison of the electrical and mechanical parameters for the two cables. The armorless SG cable used in the TAT-6 system will be used for coaxial cable parameters. A suggestion by workers from Bell Laboratories (Anderson, et al., 1980) will be used as the basis for fiber cable parameters. The capacity of the SG cable will be used for purposes of comparison. Armorless cable constituted 93% of the TAT-6 line (Dawidziuk and Williamson, 1979).

<u>SIZE</u>: The coaxial cable is large because its attenuation increases with increasing frequency and decreases with increasing size. The SG cable has attenuation at seabottom, described by the following:

$$\alpha = 0.745 \sqrt{f} + 0.0096 \; f \; \text{dB/km}$$

where f is in MHz. The square-root term is introduced by the resistive losses of the copper, whereas the linear term is from the dissipation in the dielectric material filling the guide. The dielectric loss is only a minor part of the total loss ($\sim$ 7%) at the frequency of interest (Brewer, et al., 1978). The size of the SG cable was based on an economic balance between capability, loss, and size. Figure 1, (reproduced with permission from Morse, et al., 1978) can be compared with the fiber cable of figure 2 (reproduced with permission from Anderson, et al., 1980). We note immediately that, were it not for the outer conductor of the coaxial cable, the two would be of approximately the same size. As it is, the fiber cable contains six fibers, each of which can easily handle the 4200 channels of the SG system. Yet, the outside diameter of the coaxial cable is 2.5 times that of the fiber cable.

The ratio of cross sectional areas is

$$\frac{\text{SG}}{\text{fiber}} = \left[\frac{(2.07 \times 2.54)\,\text{cm}}{2.1 \text{ cm}} \right]^2 = 6.27.$$

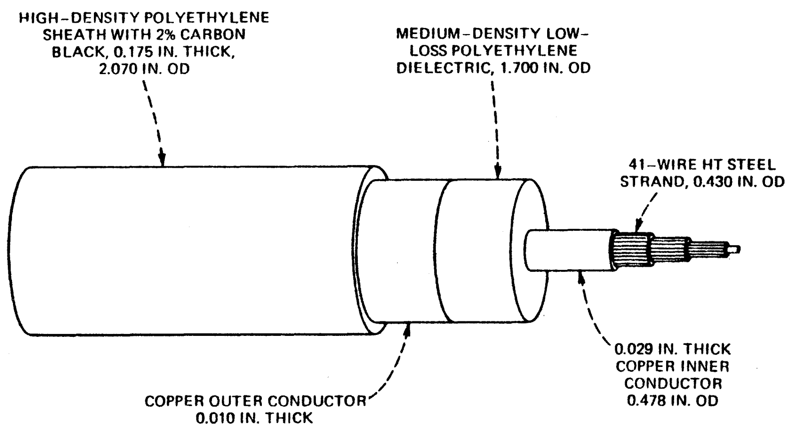

Fig. 1 Armorless SG cable. (Copyright 1978, American Telephone and Telegraph Company. Reprinted by permission.)

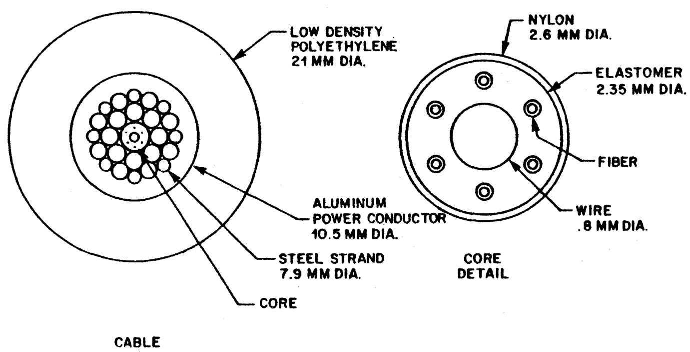

Fig. 2 Submarine fiber cable. (Copyright 1980, IEEE. Reprinted by permission.)

This can be put into perspective as follows. The Cable Ship Long Lines is able to accommodate about 1430 km of SG cable at one time (Cosier, et. al., 1978). Based on volume of the cables, the same ship could have handled (1430 x 6.27)km or 8970 km of fiber cable. Since the total link length was 6300 km, the implication is clear: based on volume, the entire line could be layed without returning to take on more cable. In some cases, the limiter is weight, not volume; in fact, weight would become the limiting factor for 6300 km of fiber cable at about 5550 lbs/km. This represents 15600 tons of cable weight. Laying ships used for intercontinental cable systems have dead-weight lift of about 8 to 10,000 tons (O'Rorke, 1980).

Cable volume influences system cost beyond the immediately apparent cost of limited cable-carrying capability. Cable-handling is eased by the six-fold reduction in cable size; cost benefits will accrue through cable-handling equipment, manpower requirements and laying speed.

WEIGHT: The SG cable weighs about 6900 lbs per km; 1350 lbs/km of this weight is attributable to the outer conductor. Thus, the outer conductor alone weights a total of 3800 tons for the 6300 km TAT-6 (one ton is 2240 lbs). The fiber cable does not require an outer conductor so the 1350 lbs/km weight advantage favors the fiber cable. Note from figures 1 and 2 that otherwise the two cables will weigh approximately the same. Aluminum is suggested as the power conductor for the fiber cable, yielding additional advantage, but this will be ignored here. The weight advantage of the fiber cable will be reflected in reduced handling, shipping, and laying cost. Note that nearly 20% of the SG cable weight is attributable to the outer conductor. That member is, of course, required for signal transmission In the case of a fiber waveguide, heavy members are required for strength and for repeater power transmission, but not for signal tranmsission. The ratio of the weights of the two cables is about 1.24:1.

CABLE COMMUNICATIONS CAPACITY: This study is based on the TAT-6 capability of 4200 two-way voice circuits, or the equivalent digital rate of 274 Mb/s. Assuming the binary pulses are gaussian shaped, the 3-dB electrical bandwidth requirement corresponding to 274 MB/s is about 103 MHz. Taking the repeater spacing to be L km, we require the fiber to have range • bandwidth capability of 103•L MHz•km, if space division multiplexing is used so traffic in the two directions is carried over two fibers. The fiber cable of figure 2 contains six fibers. This cable is capable of carrying 3X4200 or 12600 two-way voice circuits or the equivalent in voice, data, and video (822 Mb/s in each direction). The importance of the trend toward digital systems is important in this comparative study, as has already been suggested. The need to mix data and voice signals will be increasingly important in the late 1980's, as data traffic represents an ever-increasing portion of the total traffic load. Coaxial cables suffer a severe disadvantage in this regard. The finite conductivity of the copper conductors causes severe attenuation of the high-frequency components of a digital signal, thereby causing pulse distortion and limited bit-rate capability. The pulse distortion in a coaxial cable increases as the square of the length; the corresponding distortion for a fiber (worst case) increases only as the first power of the length.

REPEATERS: The sensitivity of the optical detectors was discussed in Section 2.1. It was mentioned that -36 dBm would be required to maintain 10^{-9} bit-error-rate. Assuming -3 dBm power coupled into the fiber and 3-dB margin, leaves 30 dB for waveguide loss. A reasonable assumption for cabled fiber loss, including splicer and coupling losses, is about 1 dB/km (cf. Section 2.3.1). Based on these assumptions, repeater spacing is expected to be 30 km. The fiber must have range•bandwidth product of about 3.1 GHz•km. Good quality single mode fibers are comfortably in this range at the 1300 nm wavelength. To put the suggested 30 km repeater spacing into perspective, we note that 30 km transmission has been accomplished at 800 Mb/s, 10^{11} BER and -31 dBm minimum received power with 3 dB margin (Kirkland and McDonald, 1979). Furthermore, the 30-km spacing is less than the assumed nominal spacing of 35 km used by Bell Labs planners (Anderson, et al., 1980; Runge, 1980).

The repeater spacing of 30 km is 3.16 times that of the SG coaxial cable system (9.5 km). With this three-fold reduction in the number of repeaters, we expect an associated reduction in power feed requirements. Table 3 is a summary of parameter comparison for the two cable types.

3. ESTIMATED COST COMPARISON

Table 4 lists the costs for SG coaxial cable system (TAT-6) which was put into service on July 27, 1976. The information is taken from O'Rorke (1980).

TABLE 3. Comparison of Fiber Cable and SG Coaxial Cable

Parameter	Value for fiber cable	Value for coaxial cable	Ratio Coax:Fiber	Comments
Cable Weight	5500 lbs/km	6900 lbs/km	1.25:1	Fiber weight is estimated and based on the elimination of outer coaxial conductor only.
Cable size	2.1 cm	5.26 cm	2.5:1	Variations on fiber cable size are effected as refinements in system plan evolve. Values used here are based on (Kimura, 1980).
Cable Volume (6300 km)	2200 m^3	13700 m^3	6.27:1	
Repeater Spacing	30 km	9.5 km	3.16:1	Fiber repeater spacing assumes that loss is the limiter.

*Values for the SG cable are taken from (O'Rorke, 1980; Cosier, et al., 1978).

TABLE 4. TAT-6 Costs

Component	Cost ($ Millions)
Cable (C_c)	$ 103
Submerged electronics (C_e)	78
Terminal & power feed (C_t)	5
Terminal Stations (C_t)	1
Installation (C_i)	10
TOTAL	$ 197 million

Normalized Total Cost: $7.45/ch•km*.

*TAT-6 is 6300 km, 4200 voice channels.

To estimate the total fiber cable cost, we consider the likely variation

$$C(\text{fiber}) = \alpha \cdot C_c + \beta \cdot C_e + \gamma \cdot C_t + \delta \cdot C_i \tag{1}$$

where α, β, γ, and δ are terms whose value we will estimate on the basis of the discussion in the preceding. The values of C_c, C_e, C_t and C_i are as given in Table 4; C_t is the terminal and power feed cost, including the terminal station and the terminal and power feed:

$$C_t = \$\ 6M.$$

The subscripts c, e, and i refer to cable, electronics and installation, respectively.

In the following we will estimate the cost of the fiber cable based on equation (1). The work will use constant dollars.

3.1 Cable Cost

The fiber cable being contemplated in this study contains 6 fibers, yet is smaller than the SG coaxial cable. Each kilometer of coaxial cable contains about 1350 lbs. of copper which is not contained in the fiber cable. The coaxial cable cost, from Table 4, is about $16.35/m. It seems clear that the majority of that cost is ascribable to strength members and the drawing process. The high cost is also partially influenced by the large cable size.

The fiber cable is smaller, lighter, and contains less copper, but it contains six low-loss single mode fibers. The value of α must account for the cost of those fibers with due consideration of the amount of fiber to be used;

the cable would contain 37.8 Megameters of fiber. The number of fibers and the cost of each tends to drive α to large values; the size, weight, and simplicity of the fiber cable tend to drive α toward unity. We estimate for this study, that α is between 1.5 and 2.0.

3.2 Electronics (repeaters)

The required number of repeaters is reduced by a factor of 3.16 by using fiber waveguide. Our scenario for the fiber system is based on a space division multiplexing scheme rather than frequency division scheme of the TAT-6: a fiber is devoted to each transmission direction. The complexity and cost of the TAT-6 directional filters (high-band/low-band) have cost and complexity counterparts in the spatial domain. The TAT-6 repeater draws about 8 watts; the optical repeater would probably draw much less power, especially since we assume a p-i-n detector. In addition, digital circuits tend to draw less power than analog ones. Furthermore, circuits that operate in the time domain tend to be less expensive and simpler than those that operate in the frequency domain.

Until the reliability of laser diodes is more firmly established, a submarine cable system will rely on cold spares for redundancy. This introduces cost and complexity to the repeater circuits. The associated control circuitry will increase the cost of the terminal components as well.

The scenario calls for one repeater for each of the six fibers. This allows for three fibers in each direction. The traffic capability is increased threefold, as previously discussed.

The coaxial cable system has relatively complicated submerged electronics because the cable distorts the signal in a complicated fashion. Each repeater contains equalization circuitry which matches the gain of the repeater to the loss of the cable. In shallow water, seasonal temperature variations require another level of equalization. Because cable characteristics depend on ambient temperature and depth of lay, the selection of cable and repeater is complicated and time-consuming. The ocean block equalizer is used after about 30 repeaters to perform mop-up functions because of accumulated transmission deviations. In addition, the SG system calls for four shore-controlled equalizers to compensate for cable aging. These equalizers contain directional filters and the usual compensating networks.

The electronic circuitry used in the TAT-6 system is complicated because the cable is not a stable transmssion line and because transmission characteristics vary substantially with frequency and ambient conditions. The associated circuitry for the fiber system will be much simpler because of the stability of the fiber and because the signal format is digital.

The submerged electronics for the TAT-6 cost $78M. Each of the 694 repeaters is therefore priced at $112K. This high price is tied to the demand for high reliability and to the complexity of the circuitry. The corresponding optical circuitry will be simpler but the system contains more units. There is a three fold increase in repeater spacing but each housing contains six units. The simplicity of working in the time domain rather than the frequency domain will favor the optical circuits.

We estimate the value of β to be between 1.5 and 2.

3.3 Terminal and Power Feed

The value of γ will likely be close to unity. The number of units requiring power doubles for the optical scenario, but each unit will require less than half of the 8 watts used by each TAT-6 repeater. Because of the complexity of the equalizer circuits for the TAT-6, expensive terminal components are called for. In the calcuations below, we assume $\gamma = 1$.

3.4 Installation

The cost of installing a fiber system will be less than for the TAT-6 system. The reasons are evident from Table 3. We estimate the following

$$0.4 \leq \delta \leq 0.7$$

3.5 Other

The fiber system we envisage has several distinct advantages over the coaxial cable counterpart. None is amenable to financial evaluation; i.e., it is not easy to attach a cost savings to the advantage, although they will be significant as transatlantic telecommunication becomes even more prevalent in the late 1980's and early 1990's.

The trend to digital signal formats is a welcome one because of the increasing importance of data transmission. Digital transmission allows a ready mix of voice, data, and video signals without introducing expensive overhead bandwidth. The fiber system is admirably suited to the digital format. It can be used with analog signals but the advantages of digital, especially in a long-haul system, can be exploited with ease using glass fiber waveguides. Digital transmission precludes the accumulation of noise and the corresponding degradation of signal to noise ratio inherent in the tandem connection of analog amplifiers; this is accomplished through the regeneration of digital signals so noise does not accumulate.

Another advantage lies in the twofold modularity that comes with space division multiplexing via several fibers in the same cable. First, it is relatively inexpensive to add fibers to the cable. The major portion of the cable cost is in the strength members and the cabling process. In this report we have assumed six fibers in the cable. A twelve-fiber cable would cost less than twice as much, yet the capacity doubles. This all comes about because of the relatively small size of the fiber waveguides. Installation cost for the twelve-fiber cable would differ insignificantly from that of the six-fiber cable. One must of course account also for the cost of additional repeaters when the number of fibers is doubled.

The second modular aspect is tied intimately to the use of separate fibers for separate groups of signals. The system is amenable to a branch point in the ocean, allowing a leg to Great Britain, for example, and another leg to France.

A potentially significant advantage can be had with future fiber systems through the technology of wavelength division multiplexing (WDM). This would allow a dramatic increase in utilization of each fiber through the use of several optical sources, all at a unique operating wavelength. Each laser source is modulated according to the information scheduled for that wavelength. All signals are then put onto the same fiber and then separated at the other end. Devices that perform the demultiplexing function are not yet available but development is moving comfortably. When finally refined and reliable, such devices will increase the capability of a fiber system in a significant manner. The cost will be increased complexity of the terminal units. This is an advantageous trade if the cost of the cable, including installation, is a major part of total cost. Note from Table 2 that these costs amounted to more than 57% of total system cost for the TAT-6.

3.6 Cost Estimate

Equation (1) can now be evaluated on the basis of discussion in this chapter. In summary, we estimate

$$C(\text{fiber}) = \alpha \cdot C_c + \beta \cdot C_e + \gamma \cdot C_t + \delta \cdot C_i,$$

where, for this dicussion,

C_c = \$103 M, C_e = \$78 M.

C_t = \$6 M, C_i = 10 M,

$1.5 \leq \alpha \leq 2.0,$

$1.5 \leq \beta \leq 2.0,$

$\gamma \simeq 1,$

$0.4 \leq \delta \leq 0.7.$

Therefore,

$$\$282 \text{ M} \leq C(\text{fiber}) \leq \$375 \text{ M}.$$

The corresponding normalized cost is

$$\frac{3.55 \text{ dollars}}{\text{ch}\cdot\text{km}} \leq \overline{C}(\text{fiber}) \leq \frac{4.70 \text{ dollars}}{\text{ch}\cdot\text{km}} \qquad (2)$$

where a channel is understood to mean a 64 kb/s voice channel, or the equivalent. The corresponding cost of the TAT-6 system was

$$\overline{C}(\text{TAT-6}) = 7.45 \frac{\text{dollars}}{\text{ch}\cdot\text{km}} . \qquad (3)$$

Thus, based on the approximations used in this study, we expect a cost savings of from 37% to 52%. In arriving at this figure we have not attached a monetary value to the fiber advantages alluded to in the preceding section.

4. CONCLUSIONS

This report uses data for the TAT-6 coaxial cable submarine system to estimate projected cost for a glass fiber cable system. The TAT-6 was a 6300 km link between the United States and France, utilizing a 5.26-cm cable. The system was put into service on July 27, 1976, at a cost of \$7.45 per channel•kilometer. The use of a fiber system could yield a savings of 37 to 52 percent, in constant dollars, compared to the TAT-6. The technique used here assumed that each of the six fibers in the cable handles the traffic handled by the SG cable of TAT-6. The cost advantage of the fiber system is realized because the capacity increases threefold but the cost of the cable, electronics, laying and powering increases only slightly.

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This report is based on published cost figures of the TAT-6 submarine coaxial cable system which went into service on July 27, 1976. Assuming readiness of long wavelength (1300 nm) devices by the late 1980's, we project the expected cost of a fiber cable system based on the TAT-6 experience. The study shows an expected normalized cost savings (dollar per channel kilometer) of 37 to 52 percent, in constant dollars.

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