APPLICATIONS OF OPTICAL FIBER TO CATV SYSTEMS

Dr. T. M. Straus, Theta-Com
Dr. F. L. Thiel, Corning Glass Works
Dr. M. Barnoski, Hughes Aircraft

The advent of low loss optical fibers has stimulated interest in the possible application of this new technology to CATV. In addition to low loss, fiber optics offer the potential advantages of broad bandwidth, small cable size, and immunity to RFI. This study summarizes the characteristics of the fiber optic components and systems. Extrapolations of presently available cost and performance data are applied to three types of CATV applications:

(1) Relatively low data rate upstream data transmission,
(2) Super trunk type applications, and
(3) Downstream trunk and distribution of a large number of television signals.

The sensitivity of the assumed systems to parameter variations is investigated. This investigation indicates that fiber optics may have a very limited application in CATV systems within three-five years. However, both economic and technological factors must be overcome before widespread use of fiber optics can become a reality.

I. INTRODUCTION AND SUMMARY

Since the announcement of optical waveguide attenuations below 20 dB/km, optical fibers have been mentioned as a possible transmission medium for broadband networks. This paper specifically addresses such possibilities in the CATV industry. Various CATV configurations using optical waveguides are evaluated to determine their technical feasibility and estimated cost characteristics.

The Appendix to this paper summarizes the pertinent characteristics of various optical components. Optical fiber parameters which are presently available are contrasted with what is expected to be available by 1976. These assumed parameters are then applied in Section II to three types of CATV applications.

The first application considered is that of upstream data transmittal. Star and tee coupler configurations are compared. It is concluded that the use of star couplers will lead to a more cost effective system and in fact, that the costs are at least in the same ball park, given the validity of the basic assumptions, as with the use of standard sub-low equipment.

Application of fiber optics to supertrunk also appears to be technically feasible provided each TV channel is carried on a separate fiber. Both analog and digital operation is possible, although the former requires a greater number of repeaters. Costs could be comparable to present VHF techniques for up to about ten channels. For the digital system, repeaters may not be required even up to six miles. The trade-off versus microwave is similar to that between microwave and supertrunk, i.e. for short distances, the fiber would be more cost effective. However, because of the diminished distortion, an optical fiber supertrunk could reach further than standard VHF supertrunk lines.

The most difficult application for the optical fiber is in the downstream trunk and distribution of a large number of TV channels. A system employing either digital or analog modulation on the trunk, and analog modulation on the distribution with interface to the customer at video baseband, is technically feasible but appears to be prohibitively costly within the near future.

It is concluded that fiber optics may play a limited role in some CATV applications within the next three to five years, particularly with supertrunks, but that more extensive applications will have to await further cost/performance developments in a number of areas. This is particularly true of high data rate digital systems requiring D/A and A/D converters. Other unknowns include the optical interconnect hardware and the long term reliability of semiconductor laser transmitters.

II. APPLICATION SCENARIOS

A. Low Data Rate Upstream Transmission

When consideration was first given to the application of optical fiber to CATV systems, a relatively low data rate upstream transmission system, such as SRS [1], appeared to be an ideal candidate system to consider. This initial evaluation stemmed from the realization that the low data rate poses no problems whatsoever to any of the fiber optic system components. Dispersion limits on the fiber itself need hardly be considered for 1 megabit data rates. Even the simplest LED's and optical detectors are capable of responding to these low modulation rates. Thus the optical system components would be relatively inexpensive. They exist today and would be available at low prices without the need for extensive development.

Another factor in this evaluation was that the low data rates would not require as high a received signal level for acceptable system performance. Thus high coupling losses would be less of a system constraint than might otherwise be expected.

Finally, there were problems associated with the sub-low VHF upstream data transmission which the optical system promised to avoid. These included the maintenance of adequate grounds, interference due to RF leakage into the cable system - aggravated by loose connections anywhere on the system, and interference caused by TV tuners belonging to the CATV customers who did not choose to participate on a two-way basis. Not only did the optical system avoid these problems, but also, existing upstream data transmission systems would require relatively simple design modification to substitute the optical LED and driver circuit for the sub-low transmitter and modulator.

In considering the upstream communication line, it is assumed that the optical cable is strung along the same path as the downstream coaxial cable. Although this constraint is not absolutely necessary, to violate it would be to sharply increase construction costs. Therefore, the system can be divided, as on the downstream, into the distribution and trunk portions.

The distribution system is characterized by relatively short distances but a large number of customer "taps". Several cases may be considered. As one extreme, individual optical fibers are run all the way from the customer's home to the trunk bridger. The opposite extreme is to emulate the VHF distribution and mount an optical tap near each subscriber's home. Figure 1 illustrates some of the distribution system designs which were considered.

Evaluation of the alternate systems requires first a calculation of system losses and a comparison of these losses to a permissible loss budget.

This budget can be established by estimating on the one hand the optical power which can be coupled into a single optical fiber from an LED and on the other hand by estimating the optical power required at the receiver (or repeater) for a 10^{-9} bit error rate. As much as +2 dBm of optical power has been coupled into a high numerical aperture fiber from an experimental high brightness, small size LED[2]. However, more typically one can obtain only -20 dBm to -10 dBm from currently available LED's and optical fibers.

As an optical receiver, a photodetector with avalanche gain which helps overcome thermal noise in the load resistance will yield greater sensitivity than a simple pin diode photodetector. However, the former requires more critical thermal compensation networks and will therefore be more expensive. For a 1 megabit data rate one requires -60 dBm input to a receiver employing no avalanche gain, and -70 dBm input if avalanche gain is available[3].

Combining the above two criteria one establishes a permissible loss budget of 40 to 60 dB depending on the choice of components. Ultimately, with the most advanced components a loss spacing in excess of 70 dB may be achieved.

Table I defines the parameters and indicates the nominal values assumed for this portion of the study.

Table II summarizes the loss calculations for the various cases. It is clear that of the first three cases, the lowest loss is obtained with equation (3). This is compared in Figure 2 to the loss calculated using the optical tee configuration. It is clear that the star coupler configuration is not only greatly superior to the tee configuration, but also that the technical feasibility seems well established even for fibers having as much as 24 dB/mile insertion loss. These points are further underscored when one recognizes that the assumption, t = 1 dB, and the assumed optimum use of variable fraction tee couplers are both highly optimistic in terms of minimizing loss. On the other hand, s 8dB has been measured with prototype star couplers.[4] In any case, equation (3) has only limited sensitivity to variation in the value of s.

The per mile costs of the distribution portion of the optical system is given in Table III. The value of m should be chosen to minimize the total cost in equation (5). In equation (6) the value of k is determined from Figure 2 assuming 24 dB/mile fiber and maximum 40 dB spacing between repeaters. The results are plotted in Figure 3 for the two assumed costs. Note that

TABLE I - OPTICAL SYSTEM PARAMETERS

			Assumed Values
n	=	number of optical sources/distribution mile	variable
m	=	number of star couplers/distribution line	optimized
D	=	distance from bridger to end of distribution line	0.6 mile
f	=	fiber loss/mile	8 dB, 24 dB, 48 dB
s	=	star coupler insertion loss	8 dB
t	=	tee coupler insertion loss	1 dB
F	=	cost of fiber/mile	\$160, \$320
S	=	cost of star coupler	\$100, \$200
T	=	cost of tee coupler	\$10
R	=	cost of repeater	\$250
d	=	spacing between bridgers	1/3 mile
k	=	number of repeaters/distribution line	as required

TABLE II - LOSS CALCULATIONS

Fig 1a; Distribution Loss = Df

Trunk Loss = s + 10 log (4nD + 1) + fd

Maximum Total Loss to Nearest Repeater:

$$L = Df + s + 10 \log (4nD + 1) + fd \qquad (1)$$

Fig 1b Maximum Loss to Nearest Repeater (Bridger):

$$L = Df + s + 10 \log \left(\frac{2}{3} nD + 1\right) \qquad (2)$$

Fig 1c; Maximum Loss to Nearest Repeater (Bridger):

$$L = Df + s + 10 \log \left(\frac{2}{5} nD + 1\right) \qquad (3)$$

Fig 1d; Maximum Loss to Bridger with no Repeater in Distribution:

$$L = Df + nDt + 10 \log \left[2 + \sum_{i=1}^{nD-2} \left(\frac{1}{\text{antilog } t/10}\right)^{i}\right] \qquad (4)$$

Above assumes that the various optical fiber inputs are combined either in a star coupler or directly on the surface of a photo diode which acts as the input stage of an optical repeater. In order to minimize the total quantity of optical fiber, the coupler in 1b is located 2/3 of the distance from the bridger to the end of the line and 2/3 of the fibers are coupled into it.

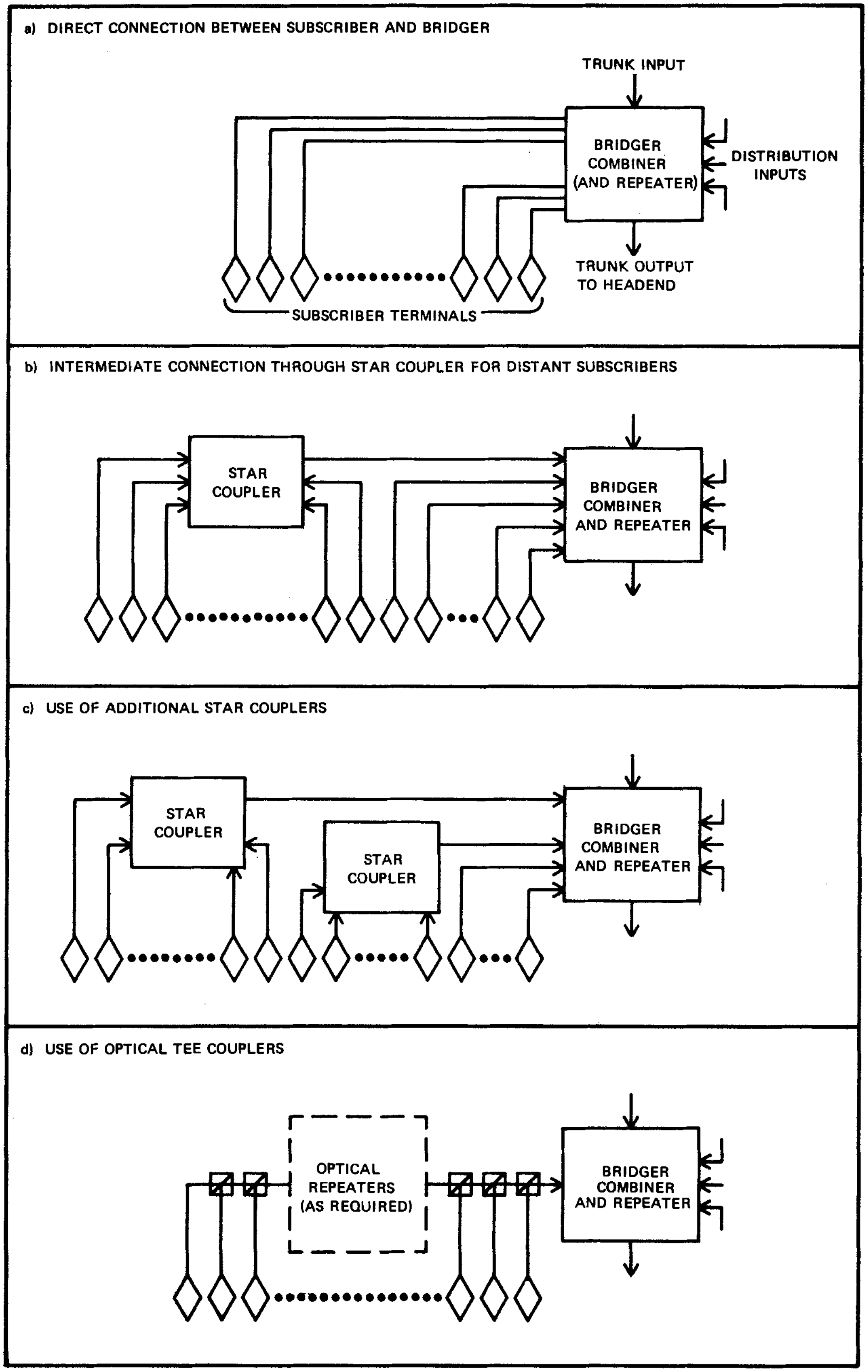


FIGURE 1 ALTERNATE FORMS OF OPTICAL UPSTREAM DISTRIBUTION

FIGURE 2 COMPARISON OF OPTICAL UPSTREAM DISTRIBUTION LOSSES USING STAR AND TEE COUPLERS

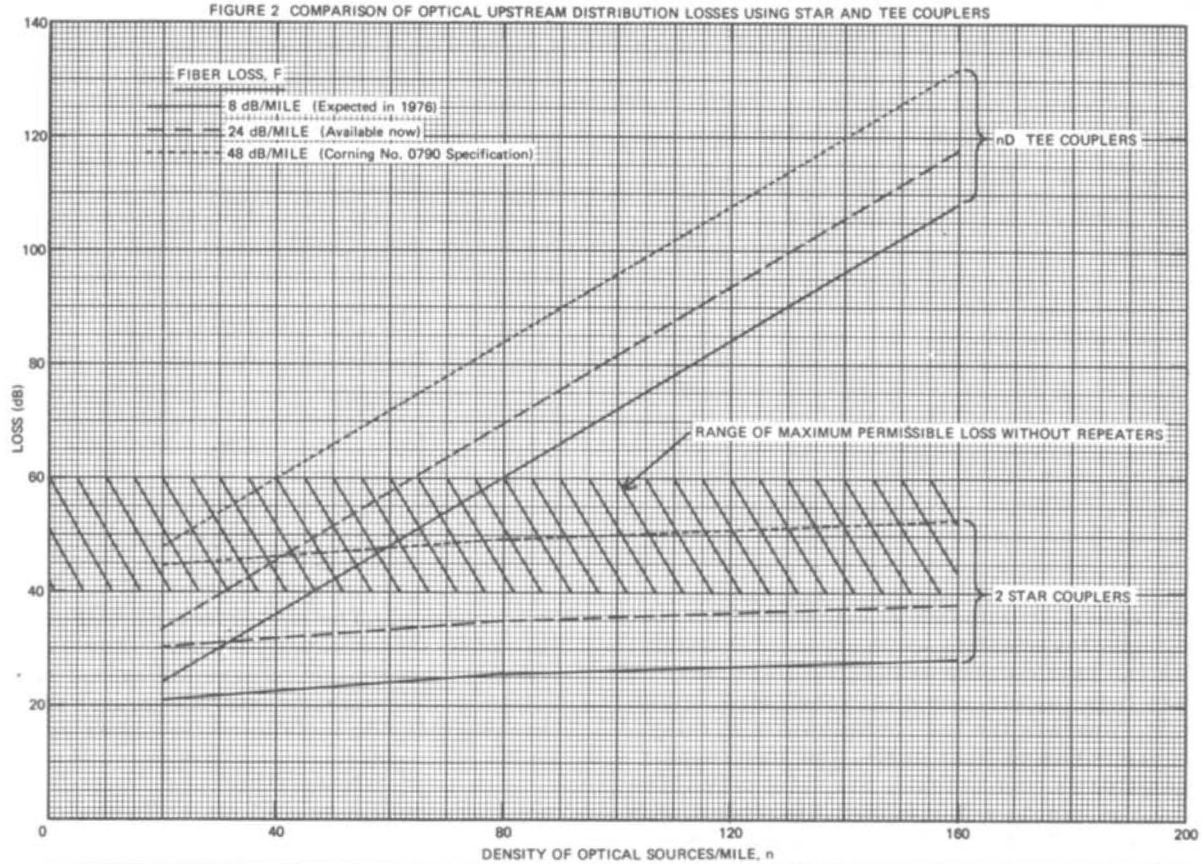


FIGURE 3 COMPARISON OF OPTICAL UPSTREAM DISTRIBUTION COST USING STAR AND TEE COUPLER STAR COUPLER

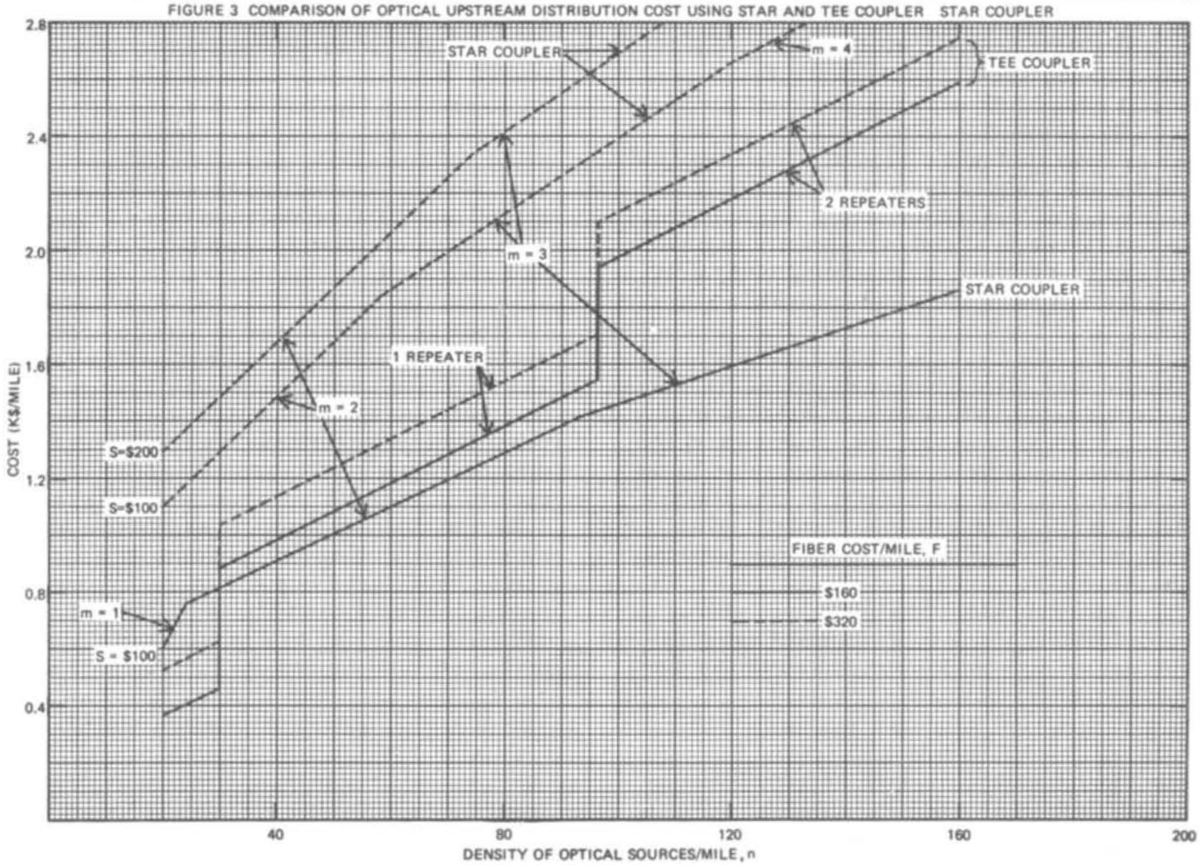


TABLE III - PER MILE COST OF OPTICAL UPSTREAM SYSTEMS

With m star couplers per distribution line:

$$C = \frac{1}{2m+1}\left[\frac{nD}{2} + \sum_{i=1}^{m} 2i\right]F + \frac{mS}{D} \qquad (5)$$

With tee couplers and with k repeaters per distribution line:

$$C = F + nT + kR/L \qquad (6)$$

Upstream trunk cost:

$$C = F + \frac{R}{d} \qquad (7)$$

as n increases, in actuality D will tend to decrease rather than stay constant as assumed. Thus the cost for the star coupler system would in fact increase less rapidly with n than indicated. Note also that, whereas the tee configuration is relatively insensitive to fiber costs, the star coupler configuration is economically practical only if the fiber cost is kept to a minimum. Therefore, it is probably essential to consider only single fiber, rather than multiple fiber bundles, in this application. Moreover, to minimize n, it would appear that pole mounted optical sources should be shared among several upstream subscribers. On the other hand, the star coupler configuration is relatively insensitive to the cost, S, of the coupler as indicated in the Figure. However, the slope of the tee coupler lines would double if the assumed value of T were doubled. The costs of the tee configuration are also indirectly tied to the value of t by the necessity of employing additional repeaters when the coupler insertion loss is increased.

Note that neither the subscriber terminal (source) cost, nor the construction cost is included in Figure 3. It may, however, be assumed that the terminal cost would be roughly comparable to the cost of a terminal using the sub-low frequency band for upstream distribution. Construction costs might well be relatively low for the optical fiber because of its lighter weight but the actual tradeoff would depend on whether or not the upstream is being added to an existing cable system and whether or not that system requires any new VHF cables and/or new line extenders.

The cost of the upstream trunk is given by equation (7) in Table III. With the parameter values listed in Table I this cost is, at worst, $1,070/mile. The cost is determined to a large extent by the repeater cost, R. Therefore, it would be reasonable to have the optical trunk cable include multiple fibers to allow for some breakage during installation and later operation.

B. Fiber Optic Supertrunk

As we have seen, optical couplers tend to have a relatively high insertion loss. Therefore, the low loss characteristic of optical fiber realizes its full potential only when applied to a long uninterrupted supertrunk line. In such an application the optical transmitter and receiver could, if necessary, be quite complex since the total system cost will be largely dependent on the optical fiber and installation costs. Thus, a wide range of possible modulation concepts may be considered.

We consider three cases in particular. The system configurations are outlined in Figure 4. The first variation of baseband analog, pictured in Figure 4a, utilizes a high power laser to permit the greatest possible non-repeatered distance while maintaining reasonably good picture quality. The output from this laser is split into the N channels to economize on transmitter costs. The only high power source which can be considered is a 2 Watt cw YAG laser. A major drawback to this laser is that the tungsten iodide lamps which are required to "pump" the laser rod must be replaced at 100 hour intervals.

The alternate analog modulation system shown in Figure 4b would not suffer this severe maintenance limitation. It will, however, require repeatering at more frequent intervals, since it

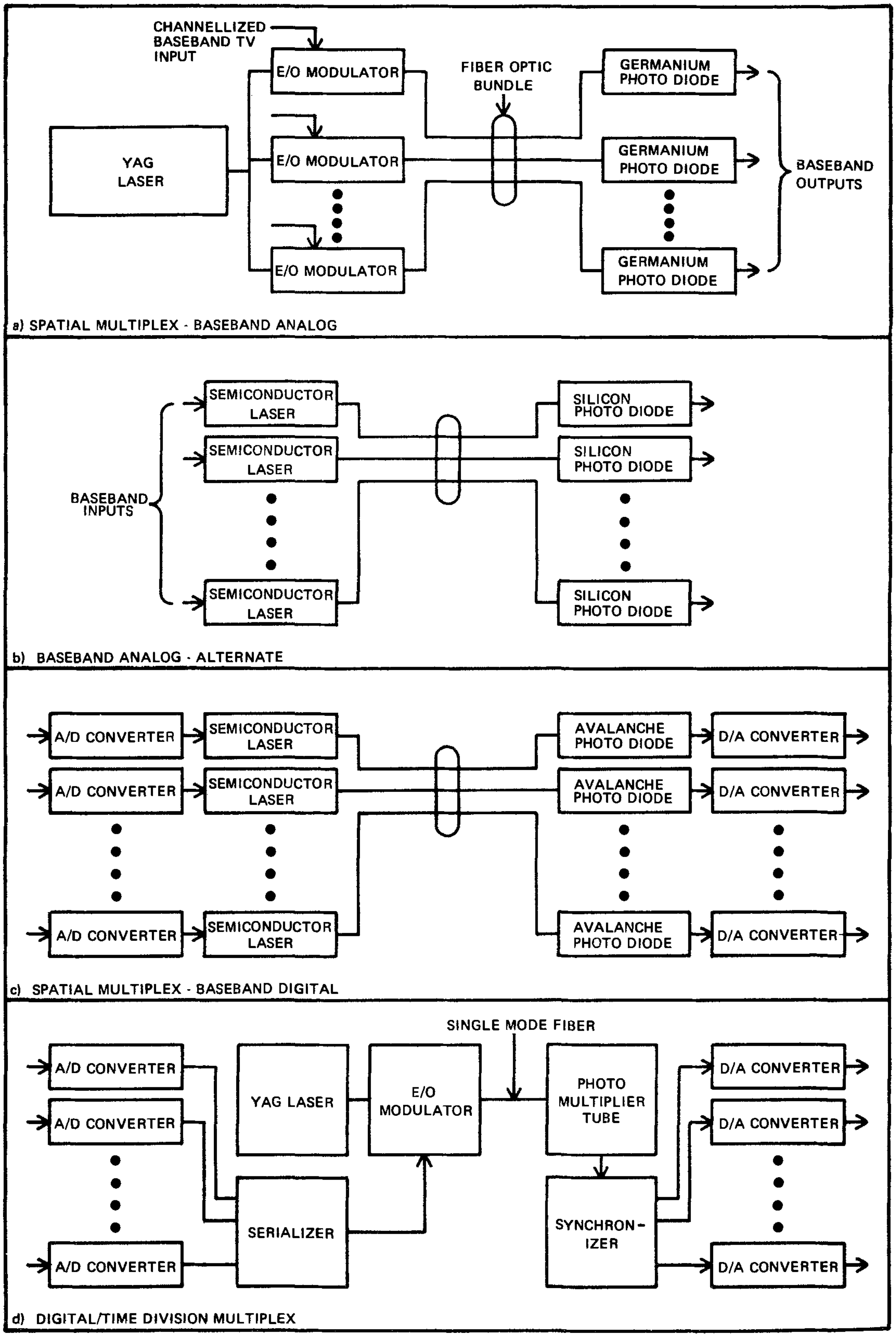


FIGURE 4 CANDIDATE SUPERTRUNK SYSTEMS

is assumed that only +8 dBm of optical power is injected into the fiber.

For the third case, baseband PCM, 80M bits/sec is a requirement for high quality color TV. The maximum super trunk distance is then 6 miles without any repeater.

The fourth case, PCM/TDM, involves equipment which today is very much state-of-the-art or beyond. If we assume up to 20 TV channels, the data rate is 1.6 Gigabits. In order to avoid the severe dispersion limit, one then requires that single mode fiber be used. One possible photodetector capable of responding to the high speed pulses is a special crossed field photomultiplier tube. Even then, because of the large noise bandwidth, a high power laser should be used to extend the range of the unrepeatered super trunk. High speed electro optic modulation has been demonstrated in the laboratory, but digital serializers and synchronizers for gigabit data rates are today simply not available.

Returning then to the cases which seem to offer the greatest practicability, Figure 5 plots the system cost versus distance for various values of N. The analog system with 10 dB/mile fiber requires 2-mile repeater spacing to obtain 60 dB S/N.

A comparison of the analog and digital system costs shows that the costs are equal between 4 and 6 miles. Since the same transmitter and receiver costs, the same fiber costs, and the same construction costs are assumed for either system, this cross-over distance is determined solely by the ratio of the converter cost to the repeater cost.

If we further assume that the digital repeater cost is comparable to the analog repeater cost, the analog system will cost more than the digital system for distances in excess of 8 miles. Moreover, one must recognize that the S/N ratio in the analog system will degrade 3 dB each time the number of repeaters are doubled. The digital system degrades much less, particularly since the repeater spacing is three times as great.

C. Downstream Trunk and Distribution

The analyses of the previous sections can serve as a guideline in determining what can and cannot be done if fiber optics are to be used for the downstream trunk and distribution of a multiplicity of TV channels. The situation is, however, more complex due to the constraints imposed by having ultimately to interface with the CATV customer's TV sets. This interface is today at VHF, but may conceivably also be with an analog baseband signal. It may, in the distant future, even require a digital input.

Figure 6 shows a possible repeater terminal configuration in which digital modulation is assumed on the trunk, and interface with the subscriber is assumed to be with analog baseband signals. The bridger terminal, which in this case is located at the trunk station repeater, converts the digital signal back to analog. It also serves as a switching center connected directly to the subscriber by means of a two-way optical fiber. The subscriber selects the TV channel by means of an upstream command which connects the subscriber-dedicated LED transmitter in the bridger to the desired baseband signal. Since the distance to the furthest subscriber is assumed to be no more than 0.6 miles, a relatively inexpensive LED and photodiode would suffice to provide the customer with a 50 dB S/N when using a 10 dB/mile insertion loss optical fiber. The total cost for fiber for each mile of distribution is nDF, assuming a fiber pair for each customer. One drawback to this scheme is that a fiber pair is needed for each additional program that is simultaneously tuned to in a given residence.

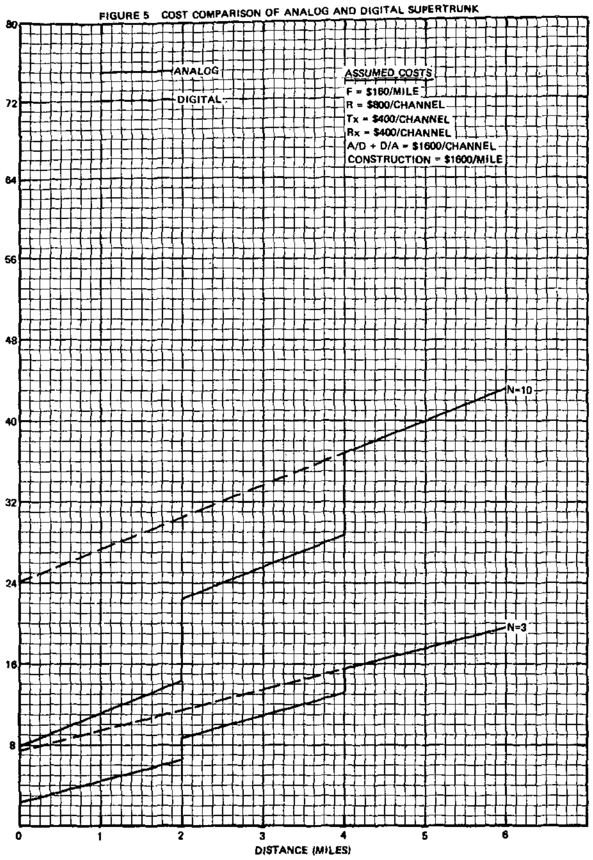
An alternative solution is to use star couplers, as with the upstream system. The costs are given by equation (5) but now multiplied by N, the number of TV channels carried by the system. In addition, the optical source at the bridger terminal must be a semiconductor laser to obtain the received power required for a minimum 50 dB S/N. Only N such lasers are required in place of the nD LED's required in Figure 6 for each arm of distribution. However, neither solution appears to be economically viable in the near future.

III. CONCLUSIONS

Fiber optics provide a potential means for providing high quality communication in CATV systems. The technical feasibility for building a fiber optic system is well established for a number of system concepts including low data rate upstream requirements and spatially multiplexed multichannel television systems. On the other hand, components required to build a truly wideband (gigahertz band width) system for CATV applications, are as yet unavailable.

Even for the relatively narrow band system solutions to important engineering problems will have to be found before implementation can take place. Foremost among these is the

FIGURE 5 COST COMPARISON OF ANALOG AND DIGITAL SUPERTRUNK



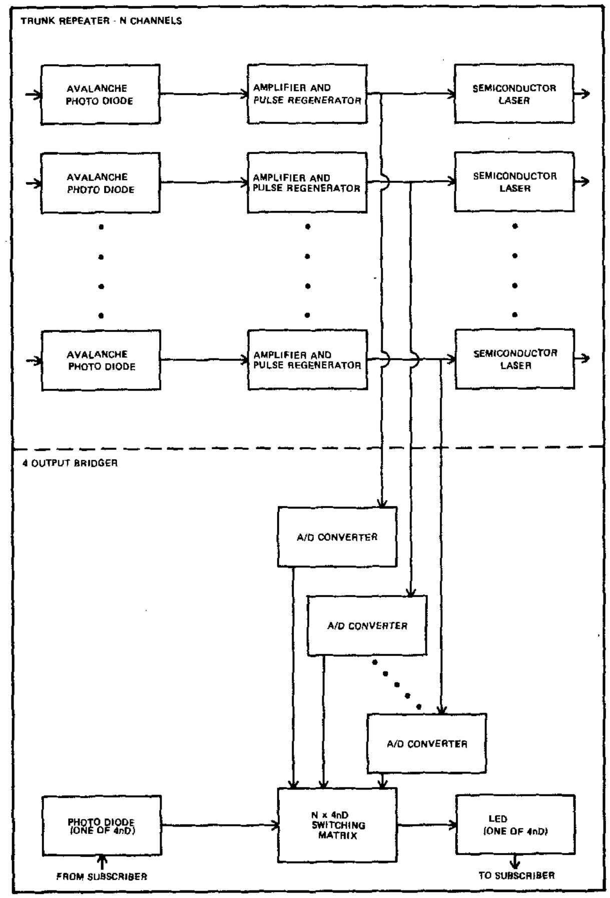


FIGURE 6 OPTICAL TRUNK REPEATER (DIGITAL) AND BRIDGER (ANALOG)

question of fiber optics cable packaging and its associated temperature effects. Other questions relate to field maintenance of a fiber optic system including fault location and the practicability of field splicing.

Economic feasibility of some fiber optic applications, particularly supertrunk for studio to headend links, has also been established provided the purposefully optimistic cost estimates made in this study can be realized. Developments within the next year or two will shed further light on the prospect for some limited applications by 1980. At this point great uncertainty still exists in both cost and performance parameters of the various system elements. On the other hand, widespread application of fiber optics in CATV systems appears to be highly unlikely until further breakthroughs are made in both technical and economic areas.

IV. APPENDIX

Background material describing the characteristics of optical waveguides is available in a number of articles (5, 6). This section assumes the reader has the general knowledge and therefore provides only information peculiar to the needs of this study.

Table IV describes the fiber parameters which are available today and what is expected to become available in the near future. This prognosis is to a large extent based on what already exists today in the engineering laboratory.

TABLE IV - FIBER PARAMETERS*

OPTICAL	Today	Near Future
Attenuation	< 15dB/km	5-7 dB/km
Dispersion (monochromatic source)		1 ns/km
(LED)		3 ns/km
Crosstalk	-60 dB	-60 dB
N. A. (peak, with graded index profile)		0.4

*See Reference 7 for packaging details, including preliminary mechanical data.

Another area under active investigation deals with cable connectors and splicing. Experimental results with cable connectors using index matching fluid shows less than 0.5 dB loss. Permanent hot splices are obtained with only 0.2 dB loss, although this is only achieved when the fiber is cut with a special apparatus and then rejoined at the same point. By careful control of production fiber parameters, it is expected that by 1976, less than 1 dB loss will be obtained in the general case. The techniques will of course have to lend themselves to field repair of the optical cable.

The power which can be coupled into a fiber from a given optical source is a function of the fiber's numerical aperture. Present step index production fibers [8] have N. A. = 0.14. The more optimistic power budgets referred to in Section IIA of this study will require a higher numerical aperture.

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