FIBER OPTIC TECHNOLOGY FOR CATV SUPERTRUNK APPLICATIONS

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ABSTRACT

A review of the optical fiber technology currently available for long-haul, multi-channel CATV interconnections, intended to provide groundwork for CATV system engineers exploring fiber optic options for their applications. Video FM coaxial transmission techniques are reviewed and compared with both analog and digital video fiber optic transmission. Performance and cost comparisons are made. The conclusion is drawn that while video FM coaxial transmission continues to have advantages, both analog and digital video fiber transmission are already attractive alternatives in some applications, and will become more so in the future.

INTRODUCTION

This presentation is not intended to be a definitive study of fiber optics, but to provide pertinent background information to CATV system engineers wishing to evaluate the fiber alternative to traditional supertrunking. It represents a collection of information from technical literature, fiber optic cable and equipment vendors who have targeted the CATV market, and CATV engineers with fiber optic experience. It was gathered while researching fiber for a specific application This information is intended as a starting point rather than an answer.

Applications for fiber in CATV may include system hub interconnects, earth station links, and advertising interconnections between systems. Much of the information presented is also applicable to systems which will be used to carry data and other kinds of information.

Optical fiber transmission of video can be cost competitive with RF transmission, depending on distance, number of channels, performance requirements, and system configuration, and is inherently more reliable. There are a growing number of systems in use, and their experience indicates that great strides have been made in the last few years in this technology.

The three alternatives that will be compared are FM video carried over traditional coaxial cables, analog video carried via fiber, and digital video via fiber.

VIDEO FM VIA COAXIAL CABLE

This technology has been in use for at least a decade and is fairly familiar in the CATV industry. A block diagram of a typical system is shown in figure 1. Video channels (with their associated audio information) are frequency modulated at different frequencies and the resulting RF carriers are combined onto one or more coaxial cables, depending on trunk bandwidth and the number of channels required. These systems typically require 12 to 16Mhz of bandwidth per video channel. Cable-powered broadband amplifiers are located every 2,000 to 3,000 feet to compensate for cable losses. The coaxial network can undergo almost unlimited branching using conventional CATV techniques. The video signals are recovered at the destination point or points through demodulation.

The performance of these systems is largely determined by the noise and distortion introduced by the cascade of trunk amplifiers. Reliability is also determined by the number of active devices in use, primarily trunk amplifiers, and by their dependence on the local power utility. Preventing ingress and egress of RF signals is of significant concern in both construction and operation.

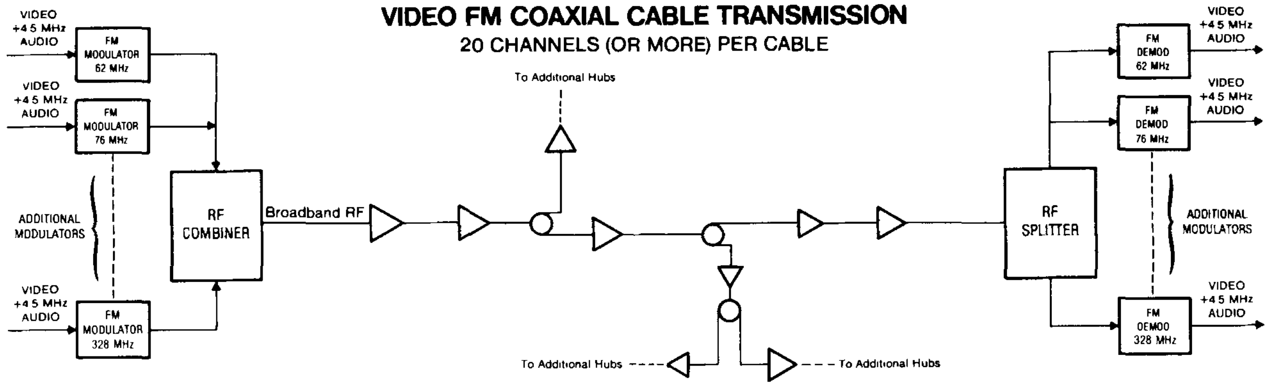
The costs of these systems, in addition to labor and supporting structures, include the cable or cables, trunk amplifiers, and power supplies, as well as the FM modulators and demodulators. There are also significant ongoing costs for trunk powering, and preventive and corrective maintenance of the amplifiers. These costs must be included in a meaningful comparison of this system with others.

An opportunity exists to optimize costs through the use of extended bandwidth amplifiers for high capacity trunks to avoid the use of a second cable, and by spacing high gain amplifiers farther apart than normal CATV practice because of the noise improvement inherent in frequency modulation. Reliability can be improved through the use of redundant amplifiers, status monitoring, and

[Figure 1]

VIDEO FM COAXIAL CABLE TRANSMISSION

20 CHANNELS (OR MORE) PER CABLE



standby power supplies.

The costs of the conventional broadband plant required are typical of CATV plant. Video FM terminal equipment typically costs about $5,000 per video circuit.

FIBER OPTIC TECHNOLOGY FOR CATV

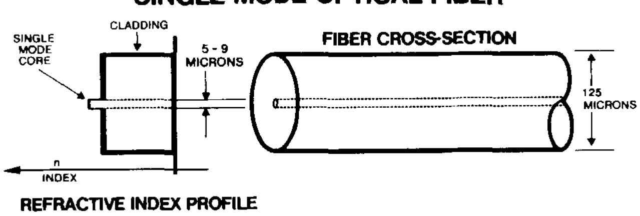
The use of optical fiber has become widespread in recent years in interconnecting telephone switching centers, among other applications. This has provided a fair amount of experience in the manufacture and installation of fiber.

Optical Fiber

An increasing amount of the fiber being installed is of the single-mode variety, with its low loss and high bandwidth. This fiber suggests itself for most CATV trunking applications.

[Figure 2]

SINGLE MODE OPTICAL FIBER

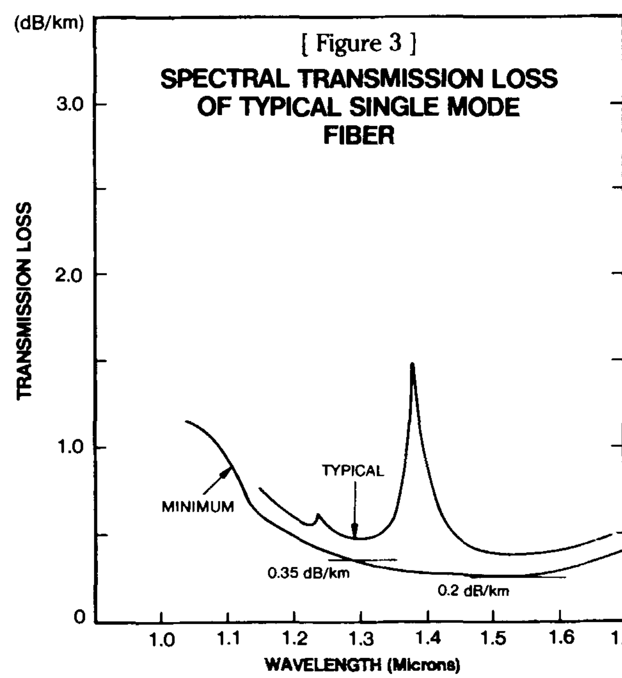


Single-mode optical fiber consists of highly refined glass which has been doped in such a way that its inner and outer cores have a different refractive index. Figure 2 shows single-mode fiber construction. While the fiber is mechanically homogeneous throughout its diameter, its refractive index undergoes a transition to define a very small light waveguide within the fiber. The waveguide diameter (5 to 9 microns) is close to the wavelength of the light being transmitted (1300 nanometers or 1.3 microns). The fiber is termed "single-mode" because the waveguide diameter has been selected to avoid multipath reflections, which create signal dispersion (time domain distortions) characteristic of large diameter "multimode" fibers. Dispersion effects are magnified with distance.

Figure 3 shows loss versus wavelength in single-mode fiber. The peaks are a function of the atomic spectral absorbtion characteristics of the glass used. The shape of the curve yields 2 "windows" of potential use centered at 1300nm and 1550nm. The 1300nm window includes the area of minimum dispersion, and the 1550nm window includes the wavelengths of lowest fiber loss.

Fiber is available today with a nominal loss of 0.5dB per kilometer at 1300nm and less than 0.4dB per kilometer at 1550nm. Somewhat lower loss fiber may be specified at additional cost.

Research indicates that the potential exists to construct fiber with losses as low as 0.16dB per kilometer at 1550nm, allowing very long fiber runs. The current record for fiber transmission in experimental systems involved transmitting data at 2 gigabits per second over 130 kilometers of fiber without repeaters.



Single-mode fiber used at both 1300 and 1550 nanometers is clearly of potential use in CATV systems, since the low loss allows long distance interconnection without repeaters, even with a certain amount of power splitting.

Fiber Cables

Fiber cables are available packaged in a variety of ways appropriate for CATV. In addition to containing different numbers of fibers, they may be ordered with different kinds of strength members, jacketing, and armoring. Cabled fiber is available in reels of 2 kilometers and more, and cabled lengths may be specified in ordering.

While the cost of single-mode optical fiber cable has come down substantially in recent years, there is still a great incentive to carry as many video signals on each fiber as possible. Costs for cable configurations appropriate for CATV applications, containing 2 to 8 fibers, range from 55 to 80 cents per fiber meter. A typical 4 fiber cable might cost approximately $0.75/ft.

Plant Construction

Cabled fiber is relatively tough, and its handling characteristics are, in most ways, as good as or better than CATV cable. Because cable lengths are large (2KM), and splices must be kept to a minimum, the penalty for error may be greater than CATV crews are accustomed to, and pulling tension and bending radius should be closely monitored. This is not to indicate that CATV engineers should be reluctant to undertake fiber projects where appropriate, but rather that the differences in technique in working with a new medium be recognized.

For the most part, normal CATV practices can be used for both overhead and underground construction. It is probably advisable to obtain experienced help from cable vendors, telephone construction personnel, or other sources when embarking on a first project.

Splicing

Single-mode splices done in a laboratory can have extremely low losses. Because of the very small diameter of the core, however, splice loss involves some element of chance.

Fibers may be spliced either with very expensive fusion devices which align and melt the fibers together, or with mechanical splices which clamp the fibers in proper alignment. While fusion splices have been favored in original construction, mechanical splices have been developed with average losses nearly as good as fusion splices. The sensible approach today may be to do initial system splicing with fusion, and to use mechanical splices for changes or repair.

Studies of many field splices indicate a mean splice loss of about 0.2dB. Once a fiber trunk has been constructed, it can be examined with an optical time-domain reflectometer (OTDR) and the relative loss of each splice can be approximately measured. Especially lossy splices can be redone until they are optimized. The time devoted to splice optimization depends on the length of the trunk and the size of the system power margin. The combined loss of fiber and splices can be measured with an optical field strength meter.

Optical Transmitters

Transmitters for fiber systems contain solid state, temperature controlled lasers. They may be modulated with either analog or digital information of a fairly wide bandwidth or high data rate. They are limited in terms of linearity, and intermodulation products are of concern, particularly in analog systems. Present transmitters are highly reliable, but laser linearity does change somewhat with aging. Because lasers are expensive, it is advantageous to share as many video signals on each laser transmitter as possible. Typical outputs coupled into the fiber are in the -3 to -5dBm range.

Optical Receivers

Optical receivers use two basic types of detectors: PIN-FET's, (field effect phototransistors) and avalanche photodiodes. While the photodiodes are potentially more sensitive, PIN-FET's are currently more widely used at 1300nm and beyond. Detector operating levels are in the -15 to -40dBm range, depending upon the type of modulation used. Because it is necessary to operate these devices close to threshold to maximize the power budget, the type of modulation selected is critical. For analog systems, wide deviation frequency modulation, similar to that used in satellite video systems, is most often used (for similar reasons). Digital systems may be operated at lower input levels because of their superior noise performance.

Detector operating levels in available systems range from -15 to -20dBm for narrow deviation FM analog systems, -25 to -30dBm for wide deviation analog systems, and -34 to -40dBM for digital systems. In digital systems, operating levels are best at lower speeds, and decrease at higher data rates.

Experimental developments in detector technology and fiber system modulation techniques promise substantial improvement in detector operating levels in the next few years. These improvements may be as great as 10 to 20dB.

System Design and Power Budgets

The assumptions behind any optical power budget depend on the type and configuration of the terminal equipment and the fiber and construction techniques to be used. Unless there are wide power margins, fiber systems must be designed with a fair amount of attention to the number of splices. This, combined with the physical constraints of cable routing, often requires that specific splice locations be designed, and that fiber cable lengths be ordered to fit the spans between those splices. Since cabled fiber is available on reels of 2 kilometers or more, the opportunity exists to greatly minimize the number of splices when power budgets require.

[Figure 4]

FIBER TRANSMISSION POWER BUDGET
(DIGITAL SINGLE-MODE SYSTEM)

Transmitter Output	-4 dBm
Detector Sensitivity	-36 dBm
TOTAL SYSTEM LOSS	32 dB
WDM Losses	3 dB
Connector Losses	1 dB
System Margin	4 dB
AVAILABLE FOR SYSTEM LOSS	24 dB

Distance @ 0.6 dB/km Path Loss: **40 km ≈ 25 mi**
(fiber & splicing)

[Figure 5]

FIBER TRANSMISSION POWER BUDGET
(ANALOG SINGLE-MODE SYSTEM)

Transmitter Output	-4 dBm
Detector Sensitivity	-28 dBm
TOTAL SYSTEM LOSS	24 dB
WDM Losses	3 dB
Connector Losses	1 dB
System Margin	4 dB
AVAILABLE FOR SYSTEM LOSS	16 dB

Distance @ 0.6 dB/km Path Loss: **27 km ≈ 16.5 mi**
(fiber & splicing)

Figure 4 shows a power budget for a digital system using moderate data rates and combining lasers onto a single fiber through wavelength division multiplexing. The 0.6dB per kilometer path loss assumes one splice every 2 kilometers, with a mean splice loss of 0.2dB. Although a system margin of 4dB has been used, careful design and construction techniques would be necessary to keep splices to a minimum and to ensure that both cable and splice losses were within specification, if such a system were used near its maximum distance.

Figure 5 shows the same power budget for a wide deviation FM analog fiber system. The only difference is in detector operating level, which illustrates the advantage of digital over analog systems. This becomes significant in links long enough to require an analog repeater, with its additional costs and its additive intermodulation and noise contribution.

Obviously, the generation of a power budget is a key step in examining fiber for a given application, and in reviewing both equipment specifications and construction plans for such a system.

Expected Developments

A number of developments will continue to make fiber more attractive for CATV supertrunking applications. Both cost and loss will improve somewhat for fiber cables. More economical circuitry will be developed capable of processing and multiplexing digital information at higher data rates. Laser costs will decrease and coupled power output will increase, allowing larger power budgets. Detector sensitivity will increase as avalanche diodes are economically produced which work reliably at longer wavelengths. New and more refined analog approaches will also be developed which may be very attractive both economically and from a performance standpoint.

A properly designed and built fiber trunk using today's dual window single-mode fibers can be expected to have a higher channel capacity in the future as new terminal equipment is developed, and as more exotic existing equipment becomes less expensive.

ANALOG VIDEO VIA FIBER

The block diagram in Figure 6 represents a practical analog video fiber optic transmission system. To maximize the number of video frequencies on a fiber, both frequency division multiplexing (FDM) (the combination of different RF frequencies) and Wavelength Division Multiplexing (WDM) are shown.

In the diagram shown, video signals are frequency modulated and combined. The center frequencies are selected to minimize intermodulation effects caused by laser non-linearities. The combined broadband signal is then used to modulate a laser, and the output of two lasers at different optical wavelengths are combined to feed a single fiber. Wavelength division multiplexers can be related to the RF diplex filters which are common in CATV. These multiplexers and de-multiplexers have some insertion loss, which can range from a few tenths to about 2dB.

At the destination, a de-multiplexer is used to separate the different optical frequencies, and two optical detectors are used. The broadband RF outputs of the detectors are split and demodulated. The FM modulators and demodulators in these systems are often identical to those which are used in video FM coaxial systems, except that they usually have wider deviations (often substantially wider) to improve detector performance.

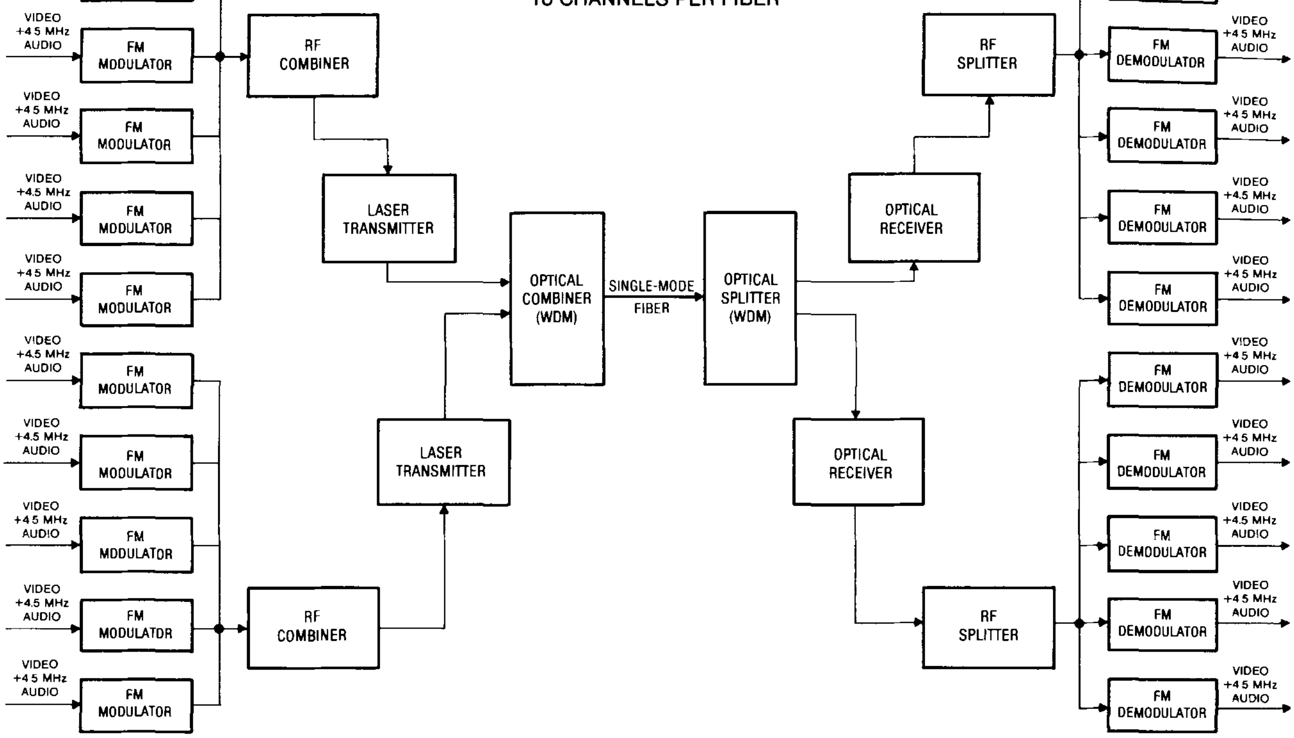
A repeater, if required, is relatively straightforward, and its effective cost depends on the number of channels being carried per fiber in the system. In the event wavelength division multiplexing is being used, de-multiplexing (and multiple detectors and laser transmitters) as well as re-multiplexing, would be required. The addition of repeaters to an analog system raises performance concerns, both in terms of video signal-to-noise ratios, and additional intermodulation products.

One technique used to achieve economies in analog optical fiber systems for earth station links is

[Figure 6]

ANALOG VIDEO FIBER TRANSMISSION SYSTEM

10 CHANNELS PER FIBER



taking the 70 Mhz IF outputs of the satellite receivers (which carry wide deviation FM video information), and frequency converting each to avoid the cost of FM modulators.

The primary performance limitations for analog video fiber systems are intermodulation products caused by laser nonlinearity, the signal-to-noise performance of the detectors, and the resulting lower power budget of these systems compared to digital systems.

Obviously, intermodulation degradation increases with the number of FM frequencies applied to each laser. Typically, between 3 and 6 frequencies are used per laser, although some systems carry more. Because laser nonlinearities change with aging, expected changes must be taken into account in examining long term intermodulation performance and effective laser life.

The cost of analog systems is currently in a state of flux. The key factors are the number of video channels per laser and the number of lasers which are combined onto a single fiber. Terminal costs for multi-channel systems are presently in the range of $7,000.00 per video circuit.

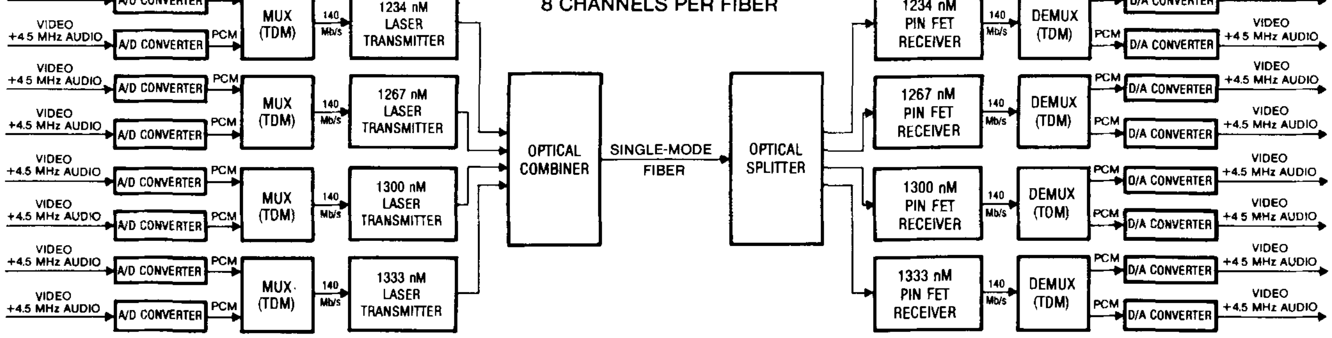
DIGITAL VIDEO VIA FIBER

Figure 7 shows a block diagram of one approach to digital video fiber transmission. Video signals are converted from analog to digital form. De-

[Figure 7]

DIGITAL VIDEO FIBER OPTIC TRANSMISSION (TDM/WDM)

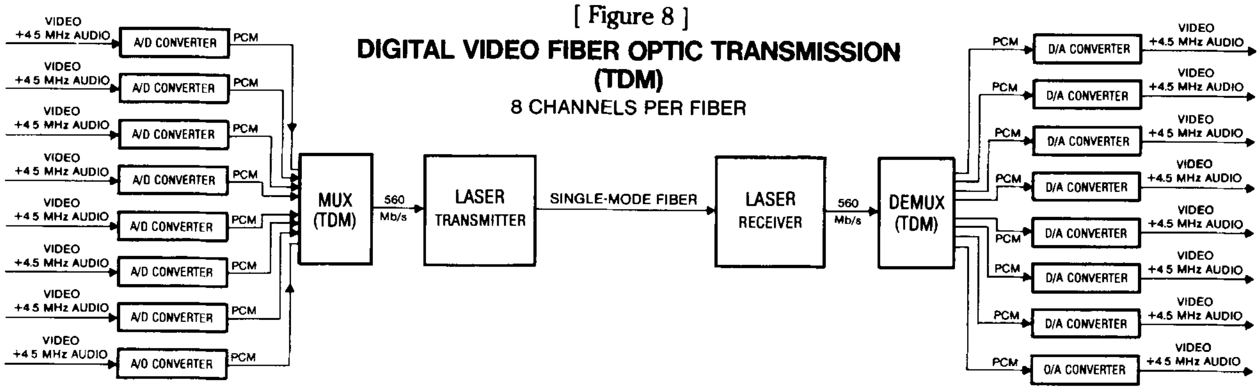
8 CHANNELS PER FIBER



[Figure 8]

DIGITAL VIDEO FIBER OPTIC TRANSMISSION (TDM)

8 CHANNELS PER FIBER



vices for this application are reliable and have been refined for video use through applications in the broadcast industry. This conversion process almost solely determines the video quality of the entire transmission link. Eight-bit encoding, which is favored by broadcasters, yields signal-to-noise ratios of approximately 63db. Seven-bit encoding (resulting in the sensing of 128 instead of 256 discrete levels) yields signal-to-noise ratios in the vicinity of 57db. In the context of most CATV transmission, this is considered sufficient. The use of seven-bit encoding allows multiplexing of a larger number of video channels in a given bandwidth at a lower cost.

Beyond the analog-to-digital conversion point, the system is processing digital pulses, and unless bit error rates become significantly higher than 10 as detector thresholds are approached, essentially all the information will be recovered with no loss in quality.

The output of two or more D/A converters can be combined into a higher rate data stream. This process is termed Time Domain Multiplexing (TDM). The multiplexed digital information is applied to a laser transmitter, and the output of two or more lasers may be combined through Wavelength Division Multiplexing (WDM) to increase the number of video channels carried per fiber.

Figure 8 shows an eight channel per fiber digital scheme which involves multiplexing together all eight videos into a high speed data stream. Systems have been built combining up to 16 8-bit encoded video channels into a 1.2 gigabit/second data stream, but are not within economic reach at present. Data rates as high as 560 megabits per second may be multiplexed through commercially available equipment.

In very long systems, where repeaters are required, digital systems are especially advantageous, since data can be received, regenerated, and transmitted transparently essentially any number of times.

At the destination, the digital data stream is recovered from the optical detector, and the individual video data streams are de-multiplexed. The analog video signal is generated through digital to analog (D/A) conversion.

The advantages of digital video fiber transmission are its relative transparency, indifference to laser nonlinearities, and improved detector sensitivity over analog methods, as well as a high degree of reliability and stability of terminal equipment, which compliments fiber's high reliability. The advantages also include the body of experience which has been gathered in telecommunications applications.

In terms of cost, digital optical systems are also in a state of flux. Systems are currently being planned which have 8 video signals per fiber, with a terminal cost of approximately $9,000 to $10,000 per video channel.

SYSTEM COST COMPARISONS

With an understanding of the trade-offs involved in the above three transmission schemes with regard to reliability, performance, branching ability, and other non-economic factors, the primary remaining factor to examine is their comparative costs.

The cost comparison graphs include the assumptions listed below. These assumptions are general, and demonstrate the dynamics of the comparison, but must be tested and changed for specific applications. In addition, changing technology and the entrance of new vendors into the market will date these assumptions rapidly. It is also assumed that physical support plant (strand, duct, hardware, etc.) labor, make-ready and construction costs are comparable for installing a fiber cable containing any number of fibers, as well as any number of coaxial cables.

Video FM/Coax

Cable, amplifiers & power supplies:	$0.66/ft.
Present value, assuming 10 yr. life and a 12% discount rate, of power (assuming average power consumption and rates) and one technician per 200 miles of plant:	$0.33/ft.

Terminal equipment costs, assuming a point-to-point system with no branching: $5000/ch.

Channel capacity per cable, assuming 14Mhz channels on a 330Mhz trunk with standard trunk amplifiers: 20 ch./cable

Analog Video On Optical Fiber

Single-mode fiber cable costs for the following configurations:

Single fiber:	$0.30/ft.
Two fiber:	$0.45/ft.
Three fiber:	$0.60/ft.
Four fiber:	$0.75/ft.
Five fiber:	$0.90/ft.

Terminal equipment costs:	$7200/ch.
Channel capacity:	10 ch/fiber
Number of miles before repeater is required:	16 miles
Repeater cost:	$2600/ch.

Digital Video On Optical Fiber

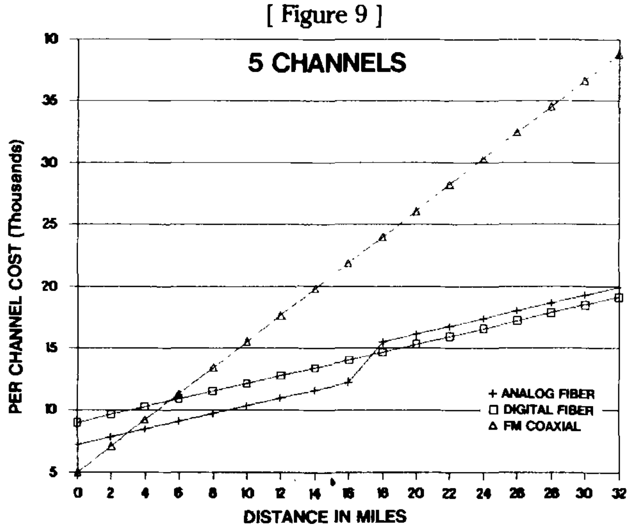
Cost of fiber cable:	Same as above
Video terminal equipment cost:	$9000/ch.
Channel capacity:	8 ch./fiber

Figures 9 through 18 are comparisons of per-channel costs for the three supertrunking approaches being discussed under various conditions. Figures 9 through 12 represent cost as a function of mileage for fixed channel loading. Figures 13 through 18 represent cost as a function of channel loading for fixed mileages.

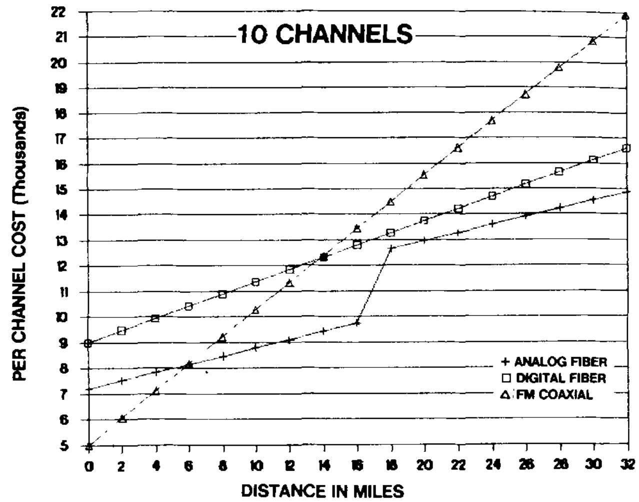
Observations

In the cost versus channel comparisons, breakpoints occur where repeaters are added to analog fiber systems. Because the per-mile cost of building and operating coaxial systems is greater than that of fiber systems, longer systems approach and exceed the per-channel cost of fiber systems.

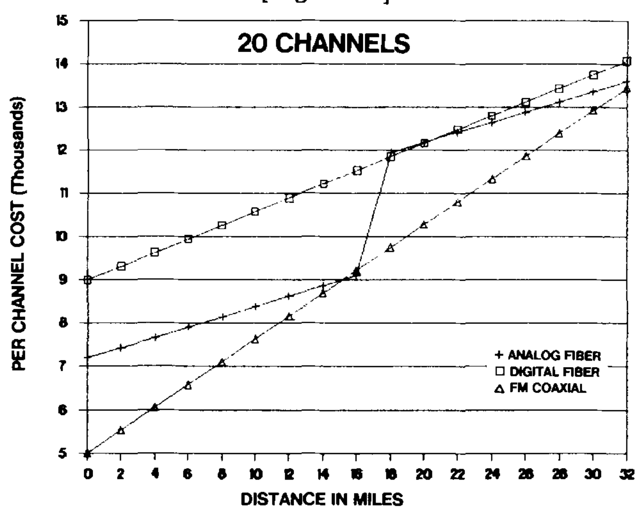
[Figure 9]



[Figure 10]



[Figure 11]



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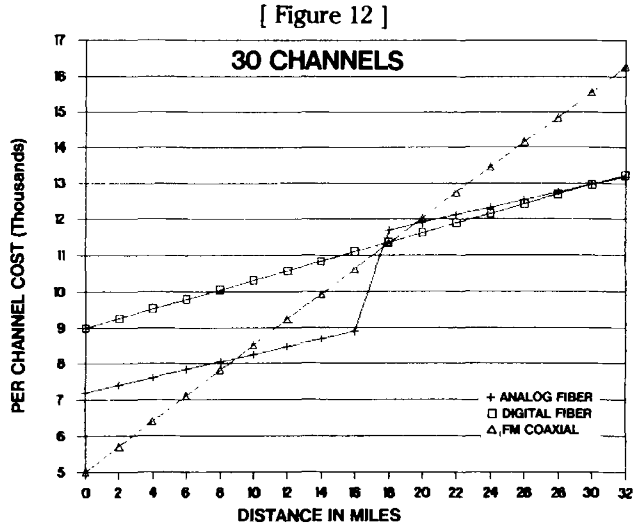
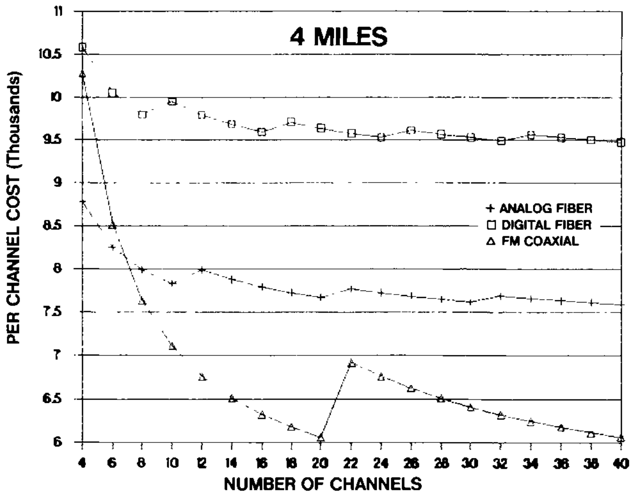
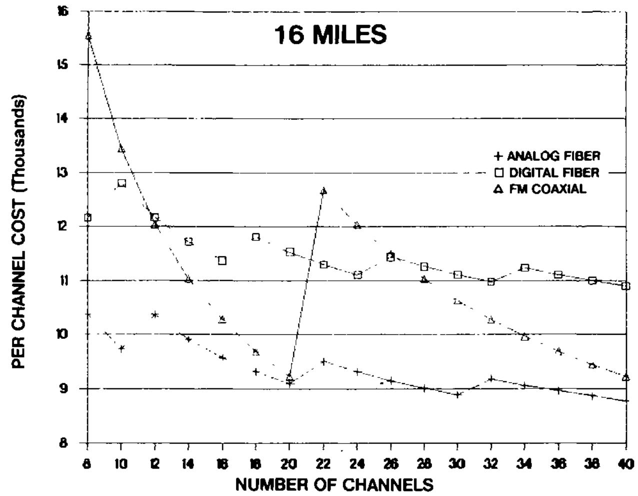


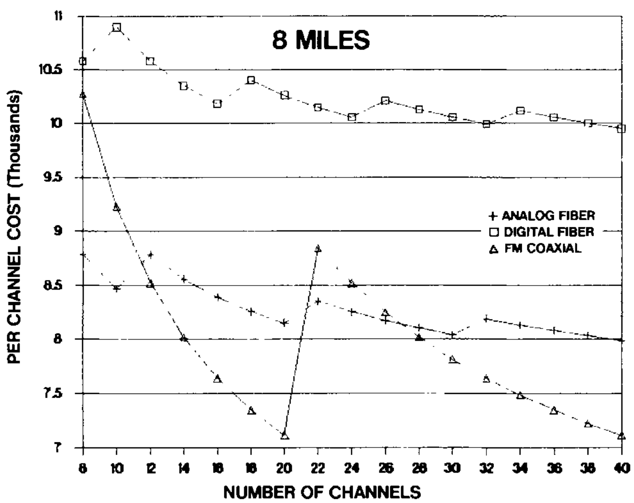
[Figure 13]



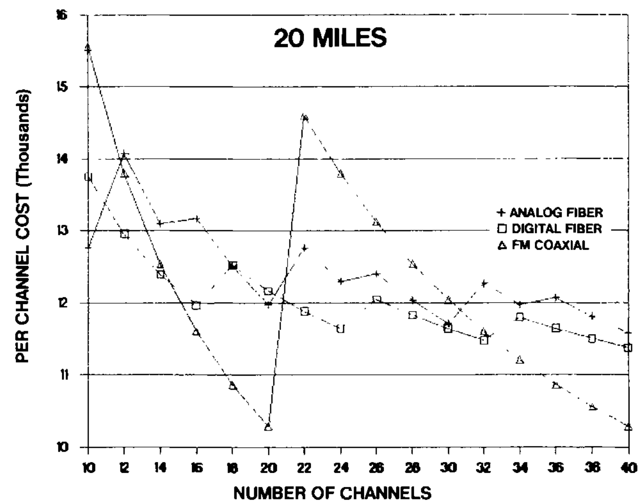
[Figure 16]



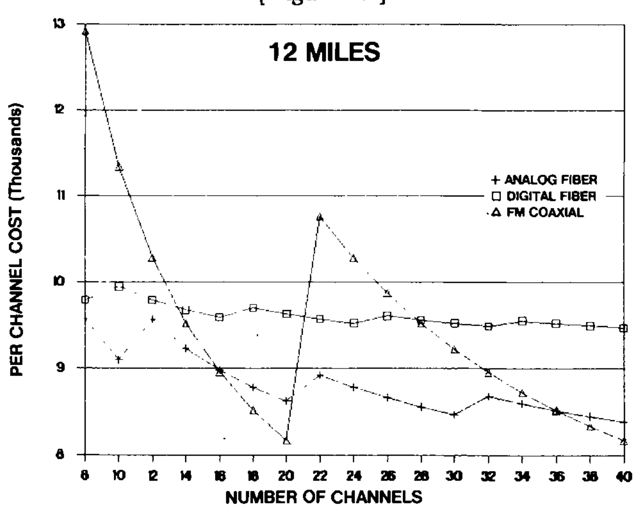
[Figure 14]



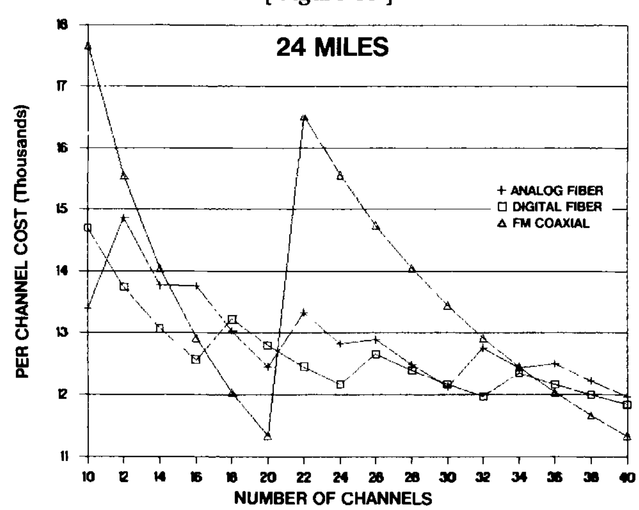
[Figure 17]



[Figure 15]



[Figure 18]



than that of fiber systems, longer systems approach and exceed the per-channel cost of fiber systems.

In the comparison of per-channel cost versus the number of channels to be transported, breakpoints occur for fiber systems where additional fibers are required. In coaxial systems, a major breakpoint occurs where it is necessary to add a second cable to carry additional channels. Video FM on coaxial cable is at its most attractive when it is heavily loaded with channels, illustrating the premium to be gained by expanding cable bandwidth before adding a second cable. Fiber systems are especially competitive for longer and more lightly loaded links.

The results shown are colored by the assumptions made, but the dynamics of the cost comparisons should be clear in demonstrating the strengths of each approach.

A Practical Example

Much of the information presented here was gathered in examining a practical application for a CATV system on the island of Oahu in Hawaii. The acquisition of a neighboring system led to a need for a high capacity interconnection between hubs on both sides on a major mountain range. Because of site access and availability problems, microwave was ruled out as an option. While video FM coaxial trunking was a possibility, the available 16 mile route passes through a rain forest and a major highway tunnel. Long power interruptions are common at the points where power would be supplied to a coaxial system. Access to trunk amplifiers was also a concern in the highway tunnel and its approaches. The length of the interconnection and the channel capacity required, as well as the reliability factor, argued strongly in favor of a fiber approach on both a cost and on a performance basis.

It is expected that a fiber link will be implemented in mid-1985. The first increment of channels will be delivered using digital transmission, and analog techniques will be tested to explore possible cost savings on additional channels, while maintaining acceptable performance.

CONCLUSION

The information presented here was gathered in evaluating a specific potential application for fiber optics. Each individual vendor has a story to tell, and it is important to develop a broad perspective if fiber is to be examined in a balanced manner. If a fiber project is being considered, it is suggested that this information be updated and supplemented with information from current vendors. It is also suggested that conversations with CATV engineers who have constructed and operated fiber systems will prove invaluable.

It is strongly recommended that a CATV engineer considering the use of fiber technology review the technical papers contained in Fiber Optic Communications, edited by Henry F. Taylor (Artech House, Dedham, MA., 1983). This excellent collection brings together a wealth of information, much of which is applicable to CATV systems.

For some combinations of distance and channel capacity fiber optic systems are the correct choice with today's technology. This may be further influenced by the relative weights given to performance, cost, and in particular, reliability. It is only fair to assume that the number of applications for fiber optics will increase with future technological developments in the field.