OPTICAL FIBER SUPER-TRUNKING

The Time Has Come
A Performance Report on a Real-World System

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ABSTRACT

A review of a specific application for video interconnection on single-mode optical fiber over a 13.9 mile path, covering system design, aerial and underground plant construction, terminal equipment selection, and operating results. Both digital and analog circuits are used in the system, and the economics and performance of the two approaches are compared. The digital equipment installed transports 4 video channels on a single-mode fiber using both 1300nm and 1550nm lasers, and the analog system is tested transporting both 8 and 12 channels per fiber. To explore the potential of the system, tests are run on a fiber path 27.8 miles (44.7km) in length. Using actual costs, an updated economic comparison between fiber optic systems and FM video coaxial systems is made.

The conclusion is drawn that analog fiber video transmission systems have been developed to the point where they offer economics and performance generally superior to, and reliability substantially better than, FM video coaxial systems. Both analog and digital fiber systems are shown to be capable of excellent quality video transmission through a path loss of over 25dB.

INTRODUCTION

The technology to make optical fiber super-trunking a practical, economical option for CATV system interconnection and other video signal transportation applications is here. Such systems are significantly more reliable than other options due to the practicality of very long, totally passive links. In an increasing number of cases, they are actually less expensive than the more traditional alternatives: microwave and FM video on coaxial cable. This paper is intended to document the construction of such a system and to draw conclusions from the performance results and economics which emerged. It is hoped that this will make the optical fiber option more accessable to the CATV industry.

In 1985, this author published a report in the NCTA Technical Papers outlining fiber basics for CATV applications and providing economic and performance comparisons between FM coaxial cable, and analog and digital single-mode fiber optic video transmission systems. The conclusions, based on the information available at that time, indicated clear advantages for each of these three technologies, but indicated that as the optical fiber field continued to mature, the balance would shift in favor of the fiber approaches. That has, to some extent, happened, as will be demonstrated through the experience documented here.

PLANNING & DESIGN

Planning

Oceanic Cablevision, Inc., currently serves 165,000 cable homes on the Island of Oahu in Hawaii. The acquisition and assimilation of an adjacent cable system made it necessary to provide an interconnection between Oceanic's headend and the new system. Because of local advertising insertions, tape importation of signals not available from satellite, tape-delay of satellite signals, and the lack of high-quality off-air reception due to an intervening mountain range, it was necessary to transport virtually all of Oceanic's signals to this system. An FM video coaxial trunk existed over part of the route, but it had insufficient channel capacity and was plagued with frequent power outages of long duration in the mountainous rain forests through which it passed. Microwave was not a serious option because of the lack of sites for a route of less than 3 hops.

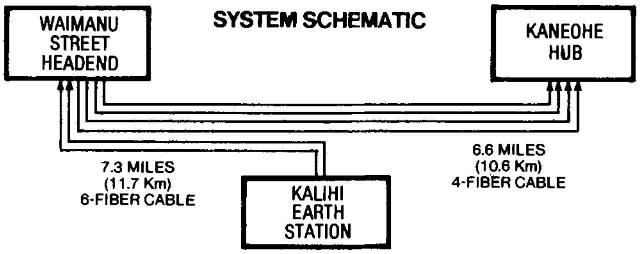
The logical route for this new interconnection passed Oceanic's earth station facilities. An FM coaxial super-trunk had been in use for some years to connect this facility with Oceanic's headend, and that trunk was in need of substantial additional capacity.

These factors combined to make a multiple-fiber single-mode optical trunk attractive to provide highly reliable capacity for transportation of additional signals from the earth station to Oceanic's headend, and of all of Oceanic's channels to the new system. The schematic in

Figure (1) demonstrates the configuration of the planned system. Two fibers were to be used to provide additional capacity from the Kalihi earth station to the Waimanu headend, and four fibers to provide signal carriage to Kaneohe, the primary hub of the newly acquired cable system.

< Figure 1 >

SYSTEM SCHEMATIC

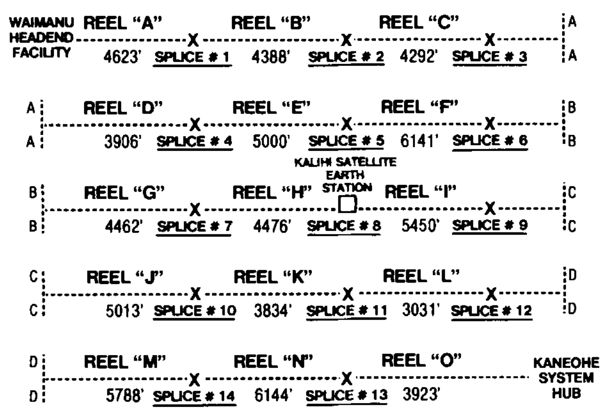


Design

The distance to be traversed was 13.9 miles (22.3km), and a design power budget was created. One necessary element in developing a power budget is a knowledge of the number of splices. Physical locations and underground pulling conditions were taken into account in selecting the splice locations, while keeping fiber reel lengths long. Figures (2) and (3) show the splice locations, and the fiber cable reel lengths which were ordered. Additional footage was ordered on each reel to allow for vertical riser pole runs, and to provide slack to make fusion splicing easier. This extra footage could also be pulled through the system to simplify repair splicing, should the system be cut in the future. The fiber order specified reel lengths to a tolerance of -0%, +5%.

< Figure 2 >

SPLICE LOCATION DESIGN



< Figure 3 >

FIBER ORDERING LIST

REEL USE LOCATION	STRAND LENGTH	REEL #	REEL LENGTH ORDERED	REEL LENGTH RECEIVED
Waimanu Street to Splice #1	4623'	A	4825'	5032'
Splice #1 to Splice #2	4388'	B	4600'	4808'
Splice #2 to Splice #3	4292'	C	4500'	4858'
Splice #3 to Splice #4	3906'	D	4125'	4461'
Splice #4 to Splice #5	5000'	E	5400'	5776'
Splice #5 to Splice #6	6141'	F	6575'	7013'
Slice #6 to Splice #7	4462'	G	4850'	5143'
Splice #7 to Earth Station	4476'	H	4900'	5264'
Earth Station to Splice #9	5450'	I	5650'	5720'
Splice #9 to Splice #10	5013'	J	5200'	5510'
Splice #10 to Splice #11	3834'	K	4100'	4339'
Splice #11 to Splice #12	3031'	L	3250'	3638'
Splice #12 to Splice #13	5788'	M	6000'	6570'
Splice #13 to Splice #14	6144'	N	6400'	7016'
Splice #14 to Kaneohe Hub	3923	O	4300'	4494

The power budget in Figure (4) reflects relatively conservative design. The budget assumes a splice loss of 0.25dB per splice; fiber loss of 0.4dB per kilometer both at 1300nm and 1550nm; connector loss at terminal equipment of 0.5dB per connector, and a total WDM diplexer loss of 6dB. The potential for future use of the same fiber at both 1300nm and 1550nm was considered an important factor. A total design path loss of 25dB, used in evaluating terminal equipment, allowed for a safe operating margin.

< Figure 4 >

DESIGN POWER BUDGET: Waimanu Street to Kaneohe

	ANALOG (1300 nm)	DIGITAL (1300 nm)	DIGITAL (1550 nm)
Laser Output:	−3 dBm	−3 dBm	−5 dBm
Fiber Loss: 22.3 Km @ 0.4 dB/Km	8.9 dB	8.9 dB	8.9 dB
Splice Loss: 14 @ 0.25 Ea.	3.5 dB	3.5 dB	3.5 dB
Conn Loss: 2 @ 0.5 Ea.	1.0 dB	1.0 dB	1.0 dB
WDM Loss: 2 @ 3 Ea.	6.0 dB	6.0 dB	6.0 dB
TOTAL LOSS	19.4 dB	19.4 dB	19.4 dB
POWER INPUT	−22.4 dBm	−22.4 dBm	−22.4 dBm
MIN. RECEIVER INPUT	−28.0 dBm	−34.0 dBm	−34.0 dBm
SYSTEM MARGIN	5.6 dBm	11.6 dBm	9.6 dBm

Fiber Selection

The fiber cable to be used was selected on the basis of both cost and availability. Because of the fact that there was substantial demand for single-mode fiber from the telecommunications industry, availability was an especially important factor. A steel strength member was specified, along with loose buffering of the fibers, in pairs, in gel-filled polyethylene tubes. A Kevlar wrapping and an outer polyethylene jacket were specified, but no armor was required since the cable would not be direct-buried at any point. The same cable was specified for both aerial and underground portions of the route.

The cable which was selected cost approximately $1.05 per foot for the six fiber portions and $0.75 per foot for 4 fibers, which equates to about $0.60 per fiber-meter. The outside diameter of the cable was the same (0.46") in either case, with one buffer tube being replaced with a solid polyethylene cord in the 4-fiber cable. The manufacturer selected, Siecor Corporation, of

Hickory, N.C., agreed to a maximum loss specification of 0.4dB per kilometer at both 1300nm and 1550nm.

Equipment Selection

The terminal equipment selected for the first phase of the project (channels which were most urgently required) was digital. Although digital equipment costs were significantly higher than analog, there was digital equipment available which was reasonably competitive, could be delivered quickly, and in which there was a high degree of confidence in performance, based on other installations. This equipment was ordered from Quante Corporation, of Santa Clara, CA.

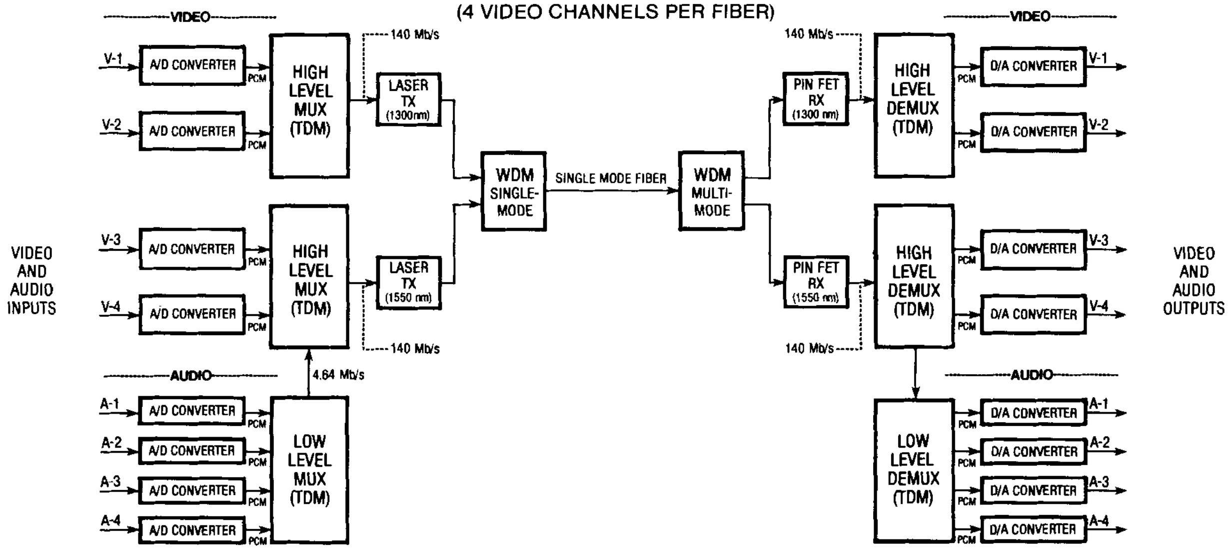
In the equipment specified, video is converted from analog to digital form with seven-bit encoding (providing 128-step amplitude resolution) and a 9.28MHz sampling rate, producing a data stream of 65MBits/sec. Audio is converted using 12-bit encoding (16-bit encoding is optional).

For the second phase of the project, providing the remainder of channels in the system, there was sufficient time to thoroughly explore analog transmission. Analog transmission was particularly attractive because it involved substantially less expensive terminal equipment, and could, with available equipment, transport significantly more video channels per optical fiber. In addition, frequency-modulated (FM) Frequency Division Multiplexed (FDM) analog video transmission on fiber is theoretically capable of excellent video performance. The primary concern with the technology was the potential effect of intermodulation products between the various FM sub-carriers due to non-linearities in both the laser and detector systems. Because of these concerns, a demonstration was arranged by the equipment vendor with the assurance that eight video channels per fiber would be delivered over a 25dB path within RS250B (medium-haul) video transportation specifications.

The manufacturer chosen was Synchronous Communications, Inc., of San Jose, CA.. The equipment specified uses 8MHz peak deviation frequency-

< Figure 5 >

DIGITAL VIDEO FIBER TRANSMISSION SYSTEM
(TDM/WDM)
(4 VIDEO CHANNELS PER FIBER)



Two video channels and up to 8 audio channels (or 16 RS-232 signals) are Time Division Multiplexed (TDM'd) together into a 140 MBit/sec. data stream. As Figure (5) demonstrates, data streams (each including two video channels and associated audio signals) are applied to one 1300nm laser and one 1550nm laser. The outputs of the two laser are combined optically in a process termed "Wavelength Division Multiplexing" (WDM), and the resulting two optical carriers, containing four video signals, are transported on one single-mode fiber. At the receive end, signals are optically separated, received with PIN-FET detectors and demultiplexed, and the base-band signals recovered. The equipment uses Lasertron lasers and QLT PIN-FET receivers. This entire process involves well understood technology and the equipment has essentially no adjustments.

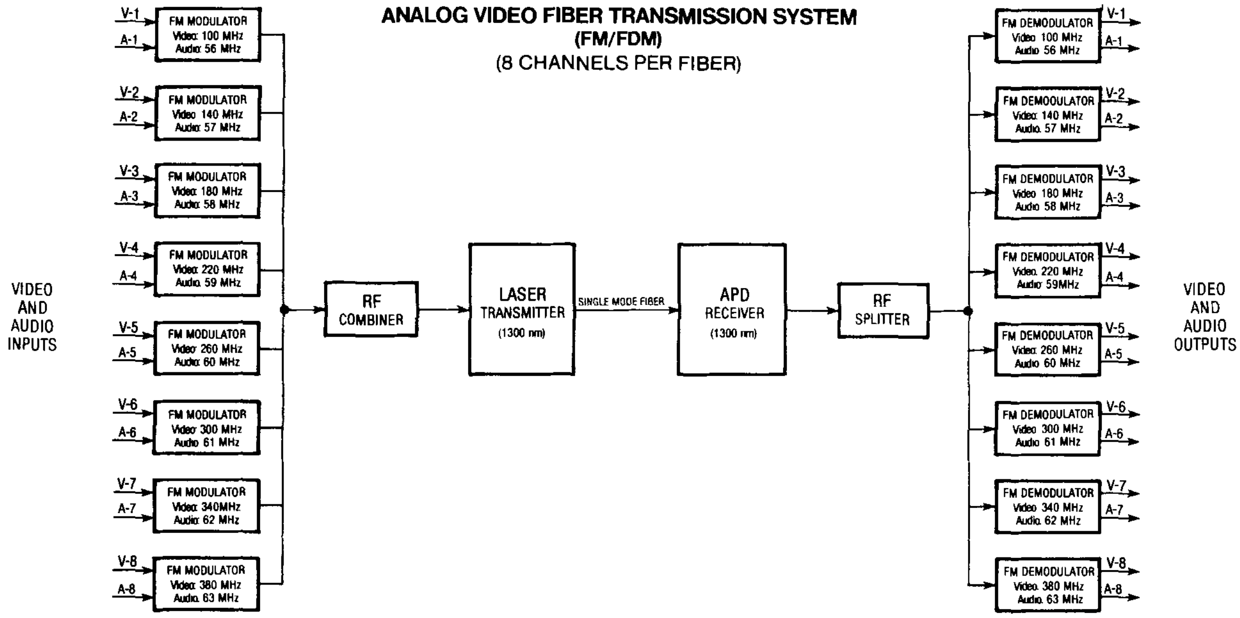
modulated video carriers, and separate frequency-modulated aural carriers. The system uses Hitachi 1300nm lasers and Fujitsu avalanche photo-diode (APD) detectors. Figure (6) shows a block diagram of the system.

The vendor dealt with intermodulation concerns in two ways. By, using very wide deviation FM, a high carrier-to-interference toleration was to be obtained. It was expected that second-order intermodulation products would have a greater effect on this system than third and higher-order products at the laser operating point selected. A frequency plan was devised whereby the center frequencies of all second-order products would fall precisely between channels. The frequency plan is illustrated in Figure (7). The channels are 40Mhz wide and channel center-frequencies are

< Figure 6 >

ANALOG VIDEO FIBER TRANSMISSION SYSTEM (FM/FDM)

(8 CHANNELS PER FIBER)



located at (N x 40)-20MHz, where N is the channel number. Thus, channel 1 would be at 20MHz, channel 2 would be at 60MHz, etc. Channels 1 & 2 were to be devoted to aural carriers, which were to be carried at levels 20dB lower than the video carriers on the system.

In this frequency plan, all additive and subtractive second-order intermodulation products will have center frequencies between channels. Thus, the additive product of channel 3 (100MHz) and channel 4 (140MHz) will fall at 240MHz, between channel 6 at 220MHz and channel 7 at 260MHz. The subtractive product between channels 3 & 4 will fall at 40Mhz, between channels 1 & 2. The effect of energy falling within a channel is proportional to the distance of the interfering signal from the center frequency of that channel. Much of the power in the second-order intermodulation products would be near their center frequencies, although these products would have a peak deviation of twice the frequency of the fundamentals, and would have energy within both adjacent channels. Figure (8) shows some of these second-order products in the spectrum.

The strength of the intermodulation products would ultimately be a result of the non-linearity of the optical devices used, but it was predicted that through this frequency plan, their effect could be minimized well below the point of visibility.

There is a temptation in frequency planning to assume that intermodulation products behave like CW carriers. Because they are the product of 2 or more frequency-modulated carriers, the deviation of the second-order products is twice that of the main carriers, and the peak deviation of higher order products is proportionately higher. While it is desirable to avoid having intermodulation product center frequencies fall in-band, it must be recognized that significant side-band energy will fall there regardless of the frequency plan. Thus, while frequency planning cannot be ignored, it is higher deviation (along with more linear optical devices) which holds the key to high performance FM/FDM fiber transmission systems.

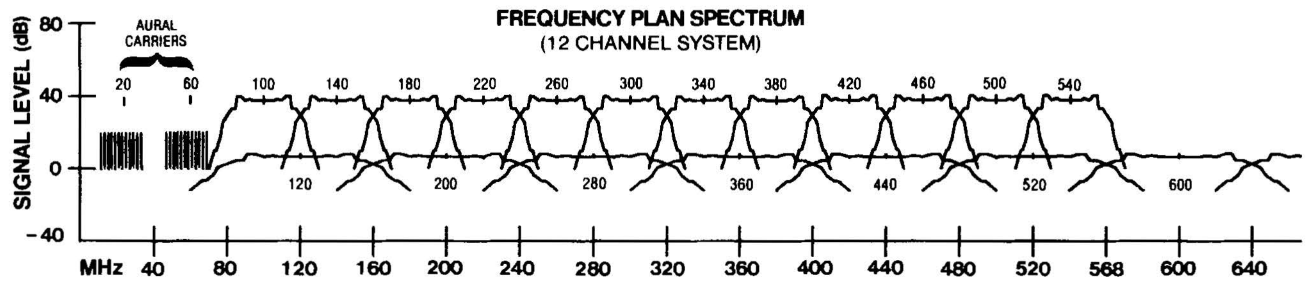
< Figure 7 >

FREQUENCY PLAN CALCULATIONS

Channel Center Frequencies shown in bold face type
2nd Order Center Frequencies shown in light face type

CH#	FREQ.	2nd ORDER INTERMODULATION COMBINATIONS
1	**20 MHz**	
	40 MHz	2–1, 3–2, 4–3, 5–4, 6–5, 7–6, 8–7, 9–8, 10–9, 11–10, 12–11, 13–12, 14–13
2	**60 MHz**	
	80 MHz	3–1, 4–2, 5–3, 6–4, 7–5, 8–6, 9–7, 10–8, 11–9, 12–10, 13–11, 14–12, 1+2
3	**100 MHz**	
	120 MHz	4–1, 5–2, 6–3, 7–4, 8–5, 9–6, 10–7, 11–8, 12–9, 13–10, 14–11, 1+3
4	**140 MHz**	
	160 MHz	5–1, 6–2, 7–3, 8–4, 9–5, 10–6, 11–7, 12–8, 13–9, 14–10, 1+4, 2+3
5	**180 MHz**	
	200 MHz	6–1, 7–2, 8–3, 9–4, 10–5, 11–6, 12–7, 13–8, 14–9, 1+5, 2+4
6	**220 MHz**	
	240 MHz	7–1, 8–2, 9–3, 10–4, 11–5, 12–6, 13–7, 14–8, 1+6, 2+5, 3+4
7	**260 MHz**	
	280 MHz	8–1, 9–2, 10–3, 11–4, 12–5, 13–6, 14–7, 1+7, 2+6, 3+5
8	**300 MHz**	
	320 MHz	9–1, 10–2, 11–3, 12–4, 13–5, 14–6, 1+8, 2+7, 3+6, 4+5
9	**340 MHz**	
	360 MHz	10–1, 11–2, 12–3, 13–4, 14–5, 1+9, 2+8, 3+7, 4+6
10	**380 MHz**	
	400 MHz	11–1, 12–2, 13–3, 14–4, 1+10, 2+9, 3+8, 4+7, 5+6
11	**420 MHz**	
	440 MHz	12–1, 13–2, 14–3, 1+11, 2+10, 3+9, 4+8, 5+7
12	**460 MHz**	
	480 MHz	13–1, 14–2, 1+12, 2+11, 3+10, 4+9, 5+8, 6+7
13	**500 MHz**	
	520 MHz	14–1, 1+13, 2+12, 3+11, 4+10, 5+9, 6+8
14	**540 MHz**	
	560 MHz	1+14, 2+13, 3+12, 4+11, 5+10, 6+9, 7+8

< Figure 8 >



Connector Selection

Connections for the system were to be fusion splices except at the terminal points, where final connection to equipment would be through WECO biconical bulkhead connectors. These connectors, while introducing significant loss and adding a certain element of unrepeatability to overall path loss, would provide points for testing and trouble shooting the system. From these points an optical time domain reflectometer (OTDR) could be used to precisely locate any future cable break.

CONSTRUCTION

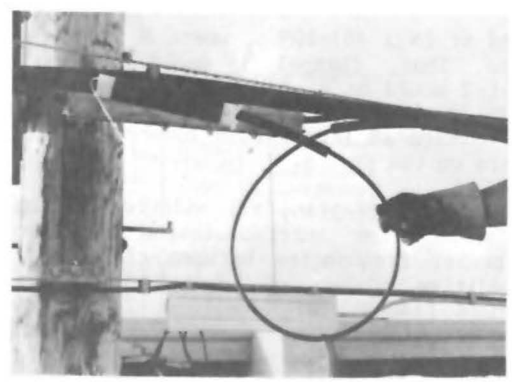
Underground Construction

All underground cable runs were located in existing conduits, either those leased from Hawaiian Telephone Company (a GTE subsidiary) or those owned by Oceanic Cablevision. In addition, most underground fiber cable was located within a "sub-duct" inside the conduit. The sub-duct used was made of polyethylene and had an I.D. of 3/4". This system of construction allowed for the placement of the sub-duct prior to fiber pulling, and any problems with conduit congestion and blockage were dealt with in advance. The fiber cable was then pulled through a completely clear path. In addition, should additional cables be pulled through these same conduits in the future, the sub-duct will provide protection for the optical fiber cable. The cost of the sub-duct was approximately $0.07 per foot.

The presence of the sub-duct made low-tension pulling relatively easy; linemen were stationed at various manholes and, with radio coordination, manually pulled the fiber into place. In this way, high pulling tensions were avoided. Once the pulling was complete, sub-duct sections were spliced using heat-shrink tubing. Figure (9) illustrates the use of such sub-duct in a section of aerial plant.

Because the cable was received on reels up to 2 kilometers in length, in most instances pulling a span from the center made more sense than pulling the entire length from one end. First, half of the span was pulled into place from the reel. Then, the remaining cable was pulled from the reel into a figure-eight shape on the ground as shown in Figure (10). After all the cable was pulled off the reel, the remainder of the span was pulled from the center, out of the figure-eight. The toughness of the fiber cable, especially when compared to aluminum-sheathed coaxial cable, was dramatically illustrated when one homeowner insisted on driving over the cable because her driveway was partially blocked. There was absolutely no visible or measureable mechanical or optical damage to the cable or any of the fibers that passed through that section.

< Figure 9 >



< Figure 10 >

Aerial Construction

One portion of aerial plant was built using standard over-lash techniques, with cable being pulled from a reel through rollers hung on an existing strand. There were no difficulties with this familiar method of construction or with the fiber cable that was handled in this way. Another portion of the system involved plant which was primarily aerial, but which followed a rather tortuous path of radical bends and short underground sections in an urban area. In this area, sub-duct was over-lashed to existing strand and coaxial cables, and was passed down riser poles and through underground sections. The fiber cable was then manually pulled as described previously. This construction method, while slightly more expensive than direct over-lash, provided easy pulling of full reel lengths and will provide for greater ease of repair should a section require removal, since the fiber cable can be pulled once again through the sub-duct.

Splicing

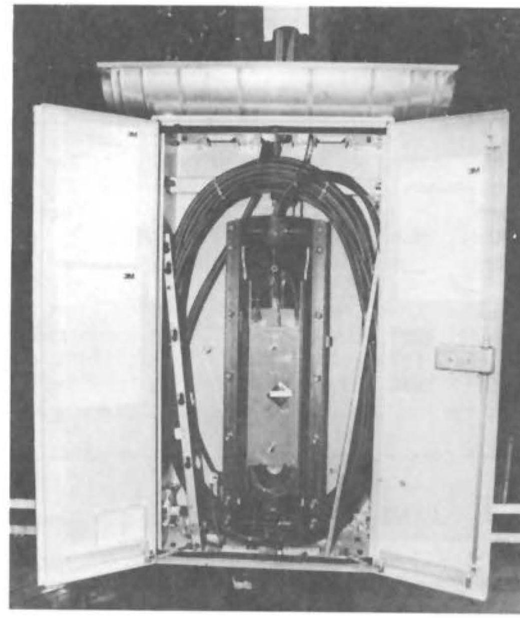
All fusion splicing and fiber testing was subcontracted to Hawaiian Telephone Company, since they had fusion splicing equipment, an optical time domain reflectometer, and trained personnel. This proved to be very satisfactory. As illustrated in Figure (11), all splicing was performed in a closed van. This was made possible by the slack which had been left at each splice location. A

< Figure 11 >

< Figure 12 >

laser injection/detection (LID) system was used to couple a small amount of light into each fiber being spliced, and to detect it on the other side of the splice. This allowed optimization of positioning prior to fusing. Underground splices were organized and sealed within a splice housing as shown in Figure (12). In many locations, these splices had to be located below ground level. Figure (13) shows the type of pole-mounted cabinet, splice housing, and splice organizing tray used in aerial sections of plant.

< Figure 13 >

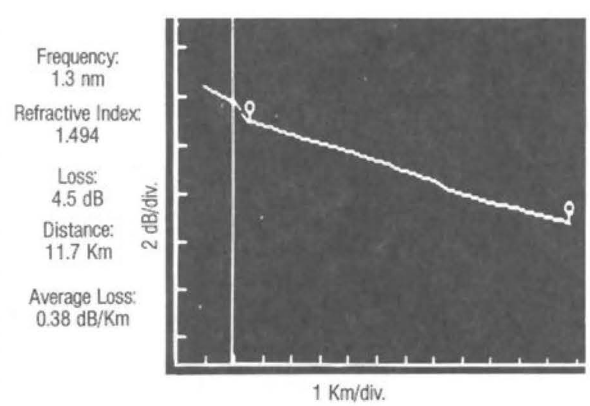


SYSTEM PERFORMANCE

Fiber Proof of Performance

Figure (14) shows an optical time domain reflectometer display of one of the 11.7km fibers from the earth station to the Waimanu Street headend. The total loss is 4.5dB. Figure (15) shows splice loss in one fiber over the route from Waimanu Street to Kaneohe, as well as the actual fiber loss. It should be noted that the average loss per splice was 0.078dB rather than the 0.25dB design specification used. These results are determined by the geometry of the single-mode core

< Figure 14 >



< Figure 15 >

FIBER AND SPLICE LOSSES
(22.3 Km / 14 SPLICES)

	AVG. LOSS	MAX. LOSS	TOTAL LOSS
1300 nm FIBER LOSS	0.36 dB/Km	0.4 dB/Km	8.05 dB
1300 nm SPLICE LOSS	0.08 dB/splice	0.34 dB	1.12 dB
1550 nm FIBER LOSS	0.22 dB/Km	0.29 dB/Km	4.91 dB
1550 nm SPLICE LOSS	0.05 dB/splice	0.29 dB	0.69 dB

within the fiber, as well as the time spent optimizing each splice. These numbers probably could have been improved slightly, but the fact that they were dramatically better than the design specification made this unnecessary.

Figure (16) shows the actual power budget which was obtained in this system. When compared with Figure (4), it is clear that the original design was over-conservative. With experience, more realistic design specifications should emerge.

< Figure 16 >

ACTUAL POWER BUDGET: Waimanu Street to Kaneohe

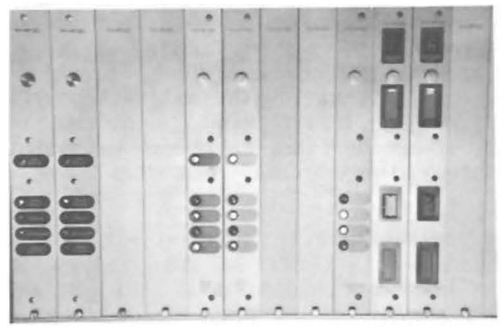
		ANALOG (1300 nm)	DIGITAL (1300 nm)	DIGITAL (1550 nm)
Laser Output:		−2.8 dBm	−1.9	−6.3
Fiber Loss:	22.3 Km	8.1 dB	8.1 dB	5.0 dB
Splice Loss:	14	1.1 dB	1.1 dB	0.7 dB
Conn Loss:	2	1.0	1.0	1.0
WDM Loss:	2	6.0	6.0	6.0
TOTAL LOSS		16.2 dB	16.2 dB	12.7 dB
POWER INPUT		−19.0 dBm	−18.1 dBm	−19.0 dBm
MIN. RECEIVER INPUT		−28.0 dBm	−34.0 dBm	−34.0 dBm
SYSTEM MARGIN		9.0 dBm	16.0 dBm	15.0 dBm

Performance – Digital Systems

Figure (17) shows the Quante digital terminal equipment installed in a rack. Performance tests for the digital system were performed with a system configuration as shown in Figure (18). Because the path loss was lower than expected, tests were done by connecting two fibers at the Kaneohe hub, and using fibers over and back as the test run. This provided a path loss of 20.9dB, with connectors, over a total distance of 27.8 miles (44.7km). Additional attenuation was inserted as shown for threshold measurements. Figure (19) shows the performance of the digital system versus the major video parameters in the RS250B (medium-haul) specification. Video signal-to-noise measurements in the digital system were performed with a Tektronix model 1430 noise test set, with a measurement limit of 59.5dB.

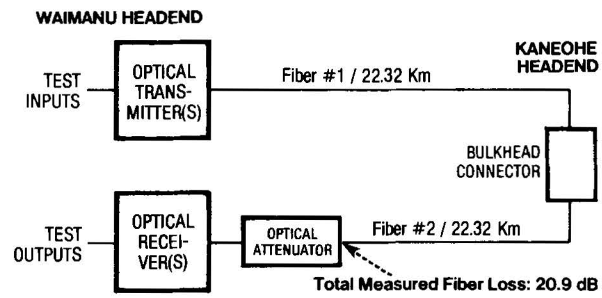
It is clear that the system meets most specifications. There are, however, compromises entailed in using 7-bit video encoding rather than the 8-bit encoding usual in broadcasting. While measurements indicated that the video signal-to-noise ratio was 60dB or better, a certain amount of quantizing noise was apparent in observing certain wave forms. This was, however, below the threshhold of perceptability. In the context of overall CATV system performance, this effect is not of great concern.

< Figure 17 >



< Figure 18 >

SCHEMATIC - TEST SETUP



< Figure 19 >

DIGITAL & ANALOG 20.9 dB LINK PERFORMANCE VS RS 250 B MEDIUM HAUL SPECIFICATIONS

PARAMETER		RS 250 B MED. HAUL		DIGITAL	ANALOG
SHORT TIME WAVE FORM DISTORTION LINE BAR EDGE OVERSHOOT		4 IRE PK-PK		2	2
CHROMA-LUM GAIN INEQUALITY		±.35 dB		0.25	0.2
DIFFERENTIAL GAIN		5%		2.5	4
DIFFERENTIAL PHASE		1.3°		1.3°	0.5°
GAIN FREQUENCY DISTORTION (MULTIBURST)		±4 IRE AT EACH FREQ.	.5 MHz	−1.5	0
			1.0 MHz	− .5	+1
			2.0 MHz	0	+1
			3.0 MHz	0	0
			3.58 MHz	−2.0	−2
			4.2 MHz	−2.5	−3
CHROMA NON-LINEAR GAIN DISTORTION	Small 20	±.4 IRE		0	0
	Large 80	±1.6 IRE		-0.2	-0.2
CHROMA NON-LINEAR PHASE DISTORTION		2°		1°	0.5°
CHROMA-LUM INTERMODULATION 50 IRE REFERENCE		1 IRE		0	0
FIELD TIME DISTORTION		3 IRE PK-PK		1	0
DYNAMIC GAIN	Line Bar	±3 IRE			0
	Sync	±1.6 IRE			0
SIGNAL TO RANDOM NOISE (WEIGHTED)		60 dB		>59	8 CHS 63.9* 12 CHS 61.5*

*AVERAGE

The measured video signal-to-noise performance of the system did not change measureably as attenuation was added to the path. At an input level of -38dBm, audio "popping" began to become apparent and, with the rising bit error rate, video impairment became noticeable in the form of missing lines. The system was unusable as soon as these degradations appeared, and -38dBm was thus considered the effective receiver threshold of the system.

It has been shown that digital systems can carry more than four video channels per fiber through higher speed Time Division Multiplexing, although, currently, the cost per channel escalates rapidly. Limiting factors in the technology currently available are the speed of the logic, lasers and detectors. As higher speed logic becomes more economically available (particularly as the Gallium Arsenide logic family matures), it should become practical to carry more digital video signals on a single fiber using a single laser and detector, within the economic constraints of the CATV industry. It should also become less expensive to use 8-bit video encoding. It is expected that all of these factors will improve the economics of digital optical fiber video transmission, and will provide some improvements in performance as well. The technical performance of the digital system tested, was, however, quite satisfactory for CATV transmission purposes.

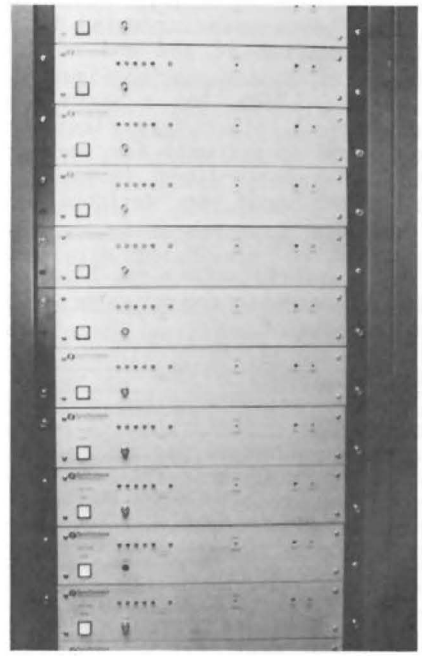
The conclusion was drawn that digital technology is presently capable of providing relatively high capacity, high quality video links over long distances. The optical margins available allow for systems with some branching loss. In addition, digital transmission lends itself very well to repeaters, with little compromise in signal quality, making very long-haul transmission practical. The Wavelength Division Mutliplexing technique demonstrated here also makes the two-way use of a single fiber a possibility, in a way directly analagous to frequency diplexed RF transmission in present coaxial systems.

Performance – Analog Systems

Figure (20) shows a photograph of the analog terminal equipment used. The test methodology was the same as illustrated in Figure (16) for the digital equipment, but measurements were also taken as a function of channel loading. Figure (19) shows the performance of this system versus the RS250B (medium-haul) specification, again with 20.9dB of path loss over 27.8 miles of fiber, and compares the results to the digital system. The system performed very satisfactorily, even when loaded with 12 channels. Video signal-to-noise ratio measurements in the analog system were performed with a Rohde & Schwarz model UPSF2 video noise meter.

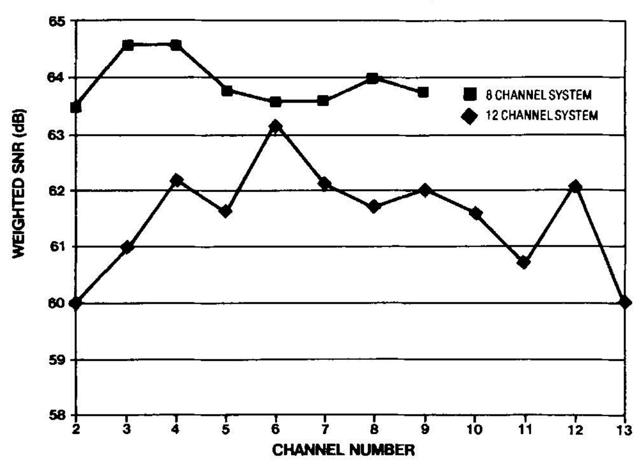
Figure (21) shows, more specifically, the change in video signal-to-noise ratio performance as the system loading over the test path was raised from 8 channels to 12. The signal-to-noise performance, while remaining satisfactory, decreased as the number of channels was increased, with the resulting reduction in transmit power on each channel (the optical power output of the laser remained constant). These results were very encouraging with regard to carrying a large number of channels on a single fiber over long distances, with a high degree of transparency and reliability. All of these factors directly increase the number of applications where this technology will be economically practical in CATV systems.

< Figure 20 >



< Figure 21 >

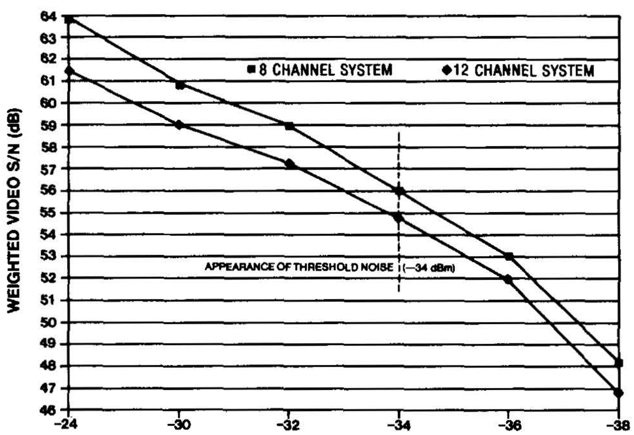
VIDEO S/N RATIO - 8 & 12 CHANNELS
(APD INPUT: −24 dBm)



One critical test was the determination of the practical noise threshhold of the avalanche photodiode receiver. Figure (22) illustrates the result. While increased channel loading decreased video SNR performance somewhat, the same practical threshhold was observed in terms of APD input, regardless of channel loading, at approximately -34dBm. These tests were conducted by inserting additional attenuation at the end of the 20.9dB fiber path. The system as configured, with a laser output of -2.7dBm, has a maximum path loss to threshhold of 31.3dB. This figure is higher than expected and speaks well for the performance of the avalanche photo-diode detector, although practical systems must be designed with some operating margin.

< Figure 22 >

VIDEO S/N RATIO VS APD RECEIVER INPUT

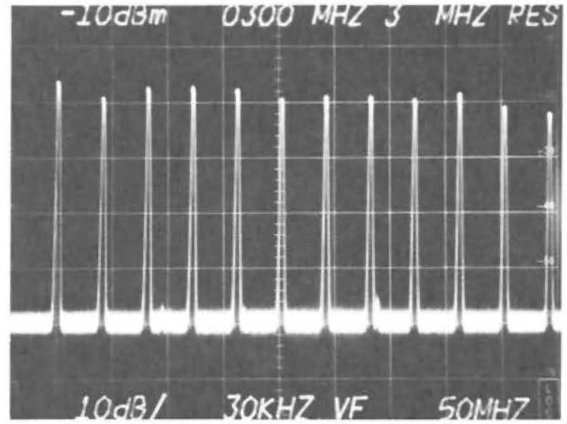


Measurement of intermodulation products was of great concern in these tests. Figure (23) shows the RF spectrum of the combined RF signals at the input to the laser transmitter. Figure (24) shows the APD output at the end of the 20.9dB test path with 12 channel loading. The second-order intermodulation product center-frequency peaks can be seen between channels, and are 30-35dB down.

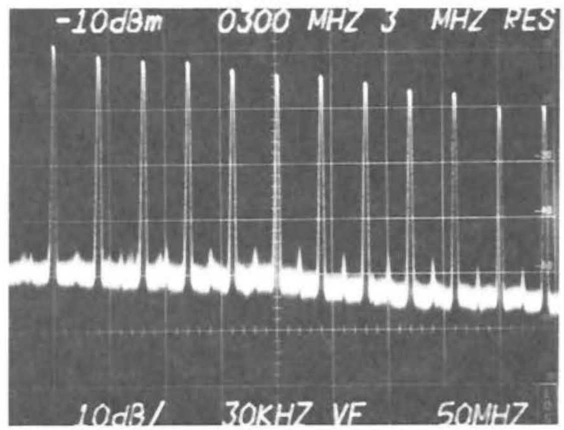
Protection ratio analysis performed by the vendor predicts that this system can tolerate, at the limit of measurable video distortion, 16MHz deviated interfering carriers which are at least 38dB down at center frequency, and at least 25dB down 20MHz from center. Figure (26) illustrates this protection ratio curve. It was prepared by measuring the beat distortion on a fixed-frequency 8MHz peak-deviated video signal, produced by an interfering signal with 16MHz peak deviation, as a function of the frequency offset of the interfering signal center-frequency. The second-order product center frequency points in Figure (24), which are offset by 20MHz and are 30-35dB down, should not produce measureable video distortion.

Figure (25) shows the system with one channel removed, so that the effect of third-order (and other odd-order) products, the center frequencies of which fall on-channel, can be observed. The sum of the odd-order products was measured to be 38-40dB down at center-frequency, and should also produce no measureable distortion. This was borne out in the video tests performed.

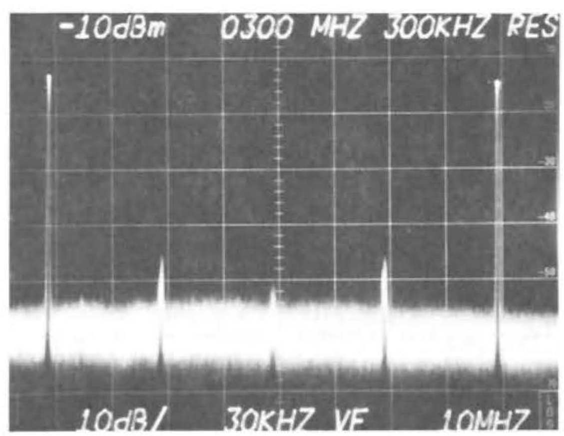
< Figure 23 >



< Figure 24 >



< Figure 25 >

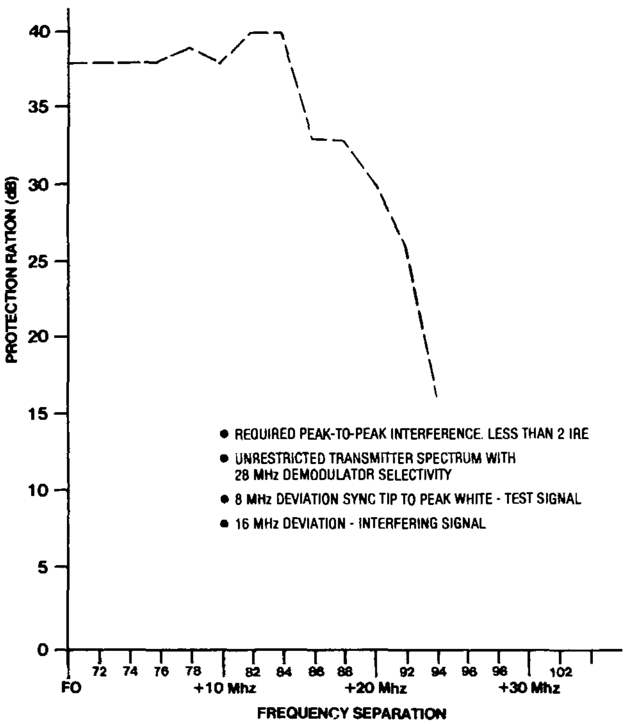


The results of the 12 channel tests leave a question as to what the ultimate limitations of this system are. One, certainly, is bandwidth. Figure (27) illustrates the frequency response characteristics of both the laser and the avalanche photo-diode. It is clear that, while it is theoretically possible to add additional channels to the system, the frequency characteristics of the optical devices will rapidly become a limitation. In addition, ultimate single-mode fiber system bandwidth is a function of the spectral purity of the laser used. This is due to the non-uniform velocity of propagation of light in the fiber as a function of frequency and the resulting dispersion effects over the distance traveled. Thus, if the laser changes frequency as it is amplitude modulated, some dispersion will result in the fiber, and an effective bandwidth limit will be established over a given fiber length. This effect was not a limiting factor in this system, despite its relatively long fiber path. It is assumed that high-purity single-mode lasers currently under development will reduce the impact of this constraint.

In summary, the system measured in the 12 channel, 20.9dB path loss test configuration seems to provide a good balance between potential performance limitations contributed by even/odd-order intermodulation products, optical device frequency response, and noise performance. The ability to carry 12 channels 30 miles or more on a single-mode fiber with relatively inexpensive terminal equipment opens many possibilities for CATV applications. When the distances that must be traversed are not so great, the relatively large power budget available may be used for branching of the system to feed a number of hubs from a single transmission point, or for the insertion loss contributed by WDM diplex filters inserted to add additional transmission capability at 1550nm (in either the forward or reverse direction). It appears probable that the CATV industry is on the verge of rapidly accelerating use of this technology because of the convergence of performance and economics.

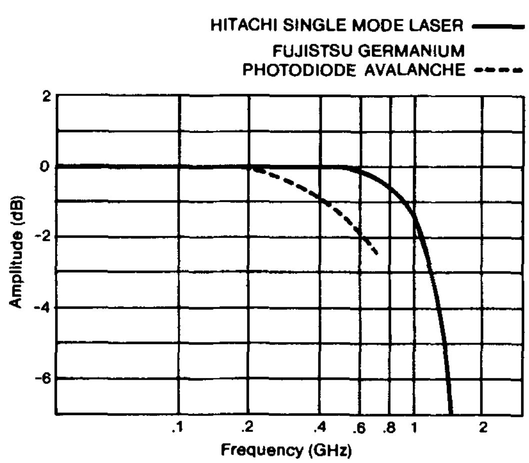
< *Figure 26* >

PROTECTION RATIO
CARRIER-TO-INTERFERENCE RATIO VS INTERFERING SIGNAL FREQUENCY SEPARATION



< *Figure 27* >

FREQUENCY RESPONSE



SYSTEM ECONOMICS

System Cost

The following are updated cost assumptions made for systems which utilize FM video on coaxial cable, and the digital and analog fiber optic transmission systems installed and tested at Oceanic Cablevision. There will, of course, be variations with each specific application.

FM, FDM ANALOG SIGNALS ON FIBER:

TERMINAL EQUIPMENT COST PER CHANNEL	$7050.00
FIBER COST:	
Single Fiber	$0.30 per/ft.
2 Fibers	$0.45 per/ft.
3 Fibers	$0.60 per/ft.
4 Fibers	$0.75 per/ft.
5 Fibers	$0.90 per/ft.
6 Fibers	$1.05 per/ft.
7 Fibers	$1.20 per/ft.
8 Fibers	$1.35 per/ft.
CHANNEL CAPACITY	12 CH/FIBER
DISTANCE BETWEEN REPEATERS	30 MILES
REPEATER COST PER CHANNEL	$6500.00

TDM, WDM DIGITAL SIGNALS OF FIBER:

(FIBER COST SAME AS ABOVE)

EQUIPMENT COST PER CHANNEL	$13645.00
CHANNEL CAPACITY	4 CH/FIBER
DISTANCE BETWEEN REPEATERS	26 MILES
REPEATER COST PER CHANNEL	$9175.00

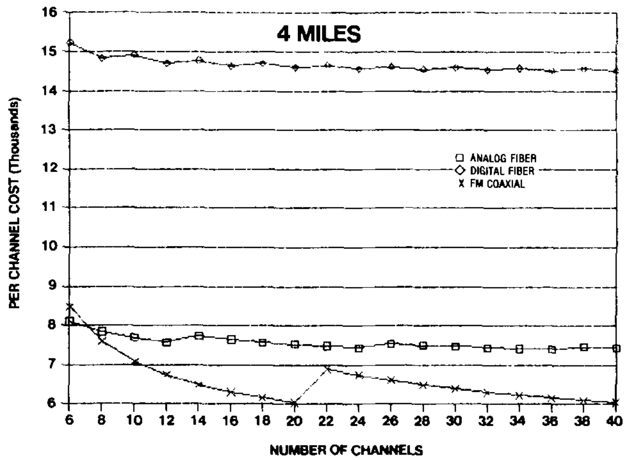
FM SIGNALS ON COAXIAL CABLE:

CABLE, AMPLIFIERS & POWER SUPPLIES	$0.66 per/ft.
PRESENT VALUE OF MAINT & POWER... (10 years, 12% annual discount rate)	$0.33 per/ft.
TERMINAL EQUIPMENT PER CHANNEL	$5000.00
CHANNEL CAPACITY PER TRUNK	20 CHANNELS

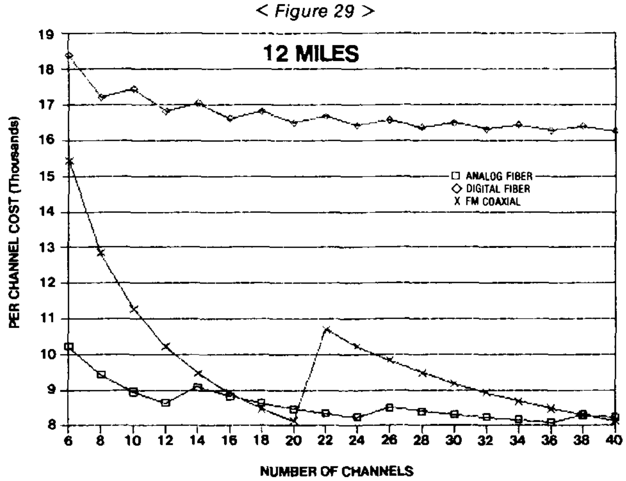
Economic Trade-Offs

The graphs in Figures (28) through (34) illustrate economic trade-offs under a variety of conditions between the three systems, based on the assumptions presented above and assuming equal labor,

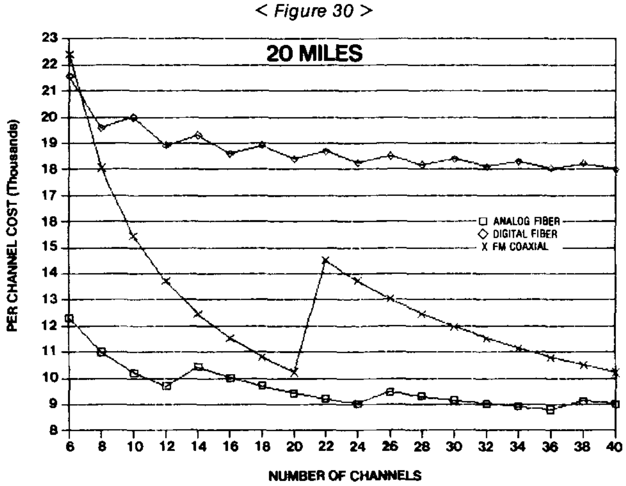
< Figure 28 >



< Figure 29 >

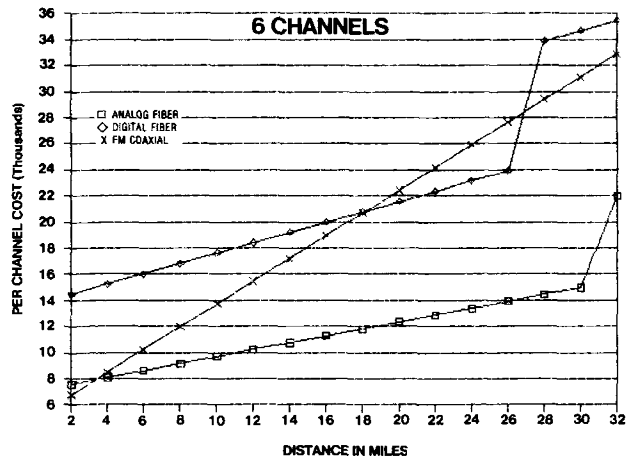


< Figure 30 >

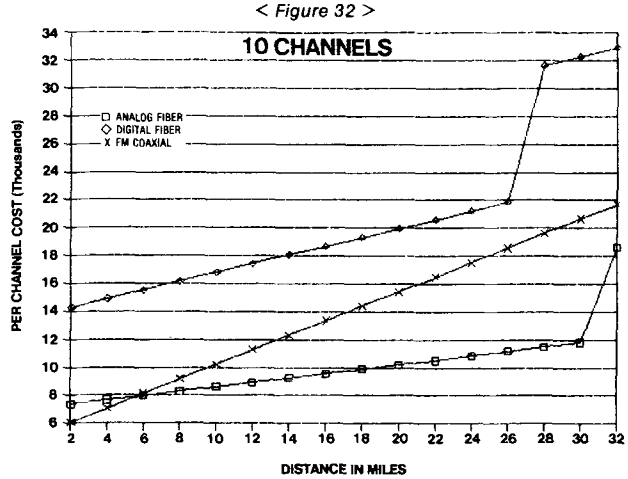


duct, and strand costs for all 3 systems. Total cost per channel is plotted against a variety of distances and channel loadings. Break-points occur where a second cable is added to the coax system for additional channels, where additional fibers and lasers are added to fiber systems, and at distances where fiber repeaters are required.

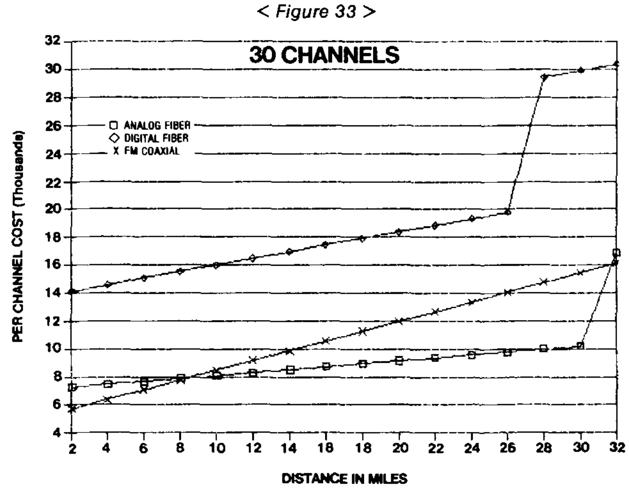
< Figure 31 >



< Figure 32 >



< Figure 33 >



It is clear that digital technology, based on the assumptions above, is attractive primarily in very long-haul applications where repeatability becomes critical. It is this technology, however, which may have the most potential for dramatic capacity increase and cost decrease in the next few years.

FM video on coaxial cable and FM, FDM video on single-mode fiber show much more closely comparable economics. While each application must be analyzed individually, it is clear that analog video transmission on fiber is often the least expensive alternative, particularly when the present value of the significantly higher ongoing operating costs of a coaxial system, with its amplifiers and power supplies, is included (as it is here).

There is an additional factor which is difficult to represent in either performance or cost comparisons between coaxial and fiber systems. That is the significantly greater reliability exhibited by fiber systems (with their smaller, tougher cable, and passive nature) over long distances. The vulnerability to amplifier, power supply, and power utility failures which are inherent in FM coaxial systems are almost entirely avoided. This factor is of greater importance as the CATV industry moves into an era of increasing competition and demand for service quality from subscribers.

CONCLUSION

The analog fiber optic system tested marks the emergence of a second generation of fiber transmission technology which is economically applicable to the CATV industry. Digital tranmission on fiber has a place today and may become a competitive alternative as digital components make advances in increasing speed and decreasing costs. Analog systems appear to be capable of performance and economics which will make them very useful for some time to come.

While FM video on coaxial cable remains a well understood, viable alternative in some applications, the number of those applications is decreasing dramatically. For point-to-point transmission of video and other CATV system signals, analog transmission via fiber is an option which simply must be considered.

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