"AN 8 KM FIBER OPTIC CATV SUPERTRUNK SYSTEM"

By

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ABSTRACT

The technical criteria for the design, analysis and hardware implementation of the first major fiber-optic digital CATV supertrunk in North America are presented.

The supertrunk system transmits 12 NTSC color television channels and 12 FM stereo channels over an eight-fiber cable 7.8 km in length. The optical fiber cable is lashed to messenger wires with optical repeaters at 2.8 km intervals. Audio, video and FM signals are digitized and multiplexed into a single 322 Mb/s bit stream modulating an injection laser diode transmitter.

1.0 INTRODUCTION

Fiber optics technology has made its debut from the laboratory to operating hardware in dramatic fashion this past year.

Major telephone companies have installed operational interoffice trunking in large cities in the U.S., Japan, and Europe. Utility firms have installed data transmission systems using optical fiber systems.

The cable television industry has also shown a high degree of interest in fiber optics systems as a possible means of increasing subscriber options through two-way telecommunications services, higher reliability and service to peripheral areas previously not cost-effective to serve. In addition, the economic projections of smaller cable, fewer repeaters, lower maintenance costs and lower capital investment have intensified CATV interest.

A wide variety of papers have been published by others speculating on what fiber optics might do for the CATV industry. This paper will describe actual fiber-optic system hardware built for a specific CATV application, i.e., a 7.8 km fiber-optic digital television trunking system. Applications to the general trunking problem will become apparent as the system is described.

2.0 SYSTEM DESIGN CRITERIA

An optimal fiber-optic trunking system is directly dependent on the trunk variables of length and performance specifications. Extensive analytical studies were done on this particular link, which carries 12 channels of color television and 12 FM stereo channels from the headend studio location to the hub distribution node. The studies made use of computer models for the transmission link using various modulation schemes.

The results of these studies showed that for a trunk length of less than 8 km, only two repeaters would be required in the link to provide studio quality video reception. The optimal modulation scheme was shown to be digital pulse code modulation (PCM) for this link, providing the best overall technical-cost performance.

An important consideration in the system design was the potential for hardware simplification offered by a fiber-optic digital repeater over conventional analog repeaters. Repeaters can be reduced to simple optical-to-electrical (and back again) regenerators for binary signals. Further, previous problems such as accumulation of intermodulation distortion (IMD) products through cascaded analog repeater chains do not exist for digital PCM video transmission systems. While such problems have limited the length of analog trunks, digital trunks have no such limitation. The net result favors digital transmission methods by providing less complex repeater modules, higher reliability, lower system maintenance costs and the potential of very long trunk lines.

2.1 System Trade-Offs

Fiber-optic repeaters can be spaced at intervals of 3 km or more, depending on fiber attenuation and dispersion characteristics.

This fact is important because fiber-optic trunk lines can reach 5 to 6 times as far as conventional coaxial systems before repeater units are required. Fiber-optic repeater lines up to 1000 km long are presently under serious consideration by major operating telephone companies.

As a general rule, fiber-optic repeaters require digital retiming (bit synchronization) in each unit to correct for the accumulation of bit errors through cascaded repeaters. For the particular 7.8 km trunking system described in this paper, analysis showed that link retiming could be accomplished effectively in the hub terminal equipment alone, and would not be necessary in the individual repeaters. Thus further equipment simplification and lower parts count were made possible in the repeater units, providing increased reliability. The overriding design goal was to design the optical repeater units as simply and straightforward as possible, since they are pole-mounted and operate in a more severe environment than the headend and hub terminal equipments.

Another important system design consideration was the trade-off of two candidate types of television signals to be encoded and transmitted, i.e., baseband video signals or vestigal sideband (VSB) signals. One well-known method of transmitting television signals is to digitally encode the baseband video, separately encode the program audio, and then combine the two data formats digitally into a single digital bit stream.

A second method of transmitting television signals which is particularly attractive to CATV applications, is to digitally encode the entire vestigal sideband spectrum. Since the VSB spectrum includes audio, picture and color subcarriers, it offers the potential of significant headend equipment cost reductions for new or updated installations.

Table 1 lists the major benefits and disadvantages of both video encoding methods. Both methods of video digitization are provided in this system to permit field tests of both implementations, on a side-by-side basis with each other and also with a conventional coaxial analog supertrunk.

Table 1. Trade-Off of Baseband Versus VSB Video PCM Encoding Methods

Baseband Video Encoding

Advantages	Disadvantages
• Lower Link Costs (3 TV channels per fiber)	• Higher Fixed Terminal Costs ("off-air" signals require demodulation to baseband)
• Lower Encoding Electronics Cost	• Total Interface Cost 3 to 4 Times Greater Than VSB Encoding

VSB Video Encoding

Advantages	Disadvantages
• Lower Fixed Terminal Costs (no demod/modulator required)	• Higher Link Costs (2 TV channels per fiber)
• Lower Total Interface Cost (direct VSB encoding)	• Higher Encoding Electronics Cost

The variables shown in Table 1 can be separated into two cost factors, fixed terminal costs and variable link costs. Fixed costs depend on the specific choices of headend and of terminal distribution equipment. Variable link costs depend on the total trunk length and the number of repeaters and fibers used in the link. Using 1981 cost projections of fixed and variable costs for both baseband and VSB PCM encoding equipments, it can be shown that the total cost of a VSB link is less than the total cost of a baseband link, if the total length is less than 20 km. In other words, two channels per fiber VSB PCM is more cost-effective than three channels per fiber baseband PCM for distances less than 20 km, because the additional terminal equipment cost for the three channels per fiber case is not offset by variable link costs until the link length exceeds 20 km.

3.0 DESCRIPTION OF THE SYSTEM

The telecommunications system described in this paper uses graded-index optical fibers having a bandwidth-distance product in excess of 600 MHz-km and attenuation less than 8 dB/km. Eight small optical fibers (0.005-inch diameter) are formed into a single multifiber cable providing transmission capacity for a full 12 TV channel supertrunk in a cable less than 1/2-inch in diameter.

Of the eight fibers, only six are actively used, allowing the two spare fibers to be used for expansion to 18 channels. The six fibers are allocated as follows:

Fiber No.	Function
1, 2	Each fiber carries three high-quality digital baseband TV channels, three digital FM stereo channels plus parity and housekeeping data.
3, 4, 5	Each fiber carries two high-quality digital VSB TV channels, four digital FM stereo channels, plus housekeeping data.
6	Fiber carries three channels of high-quality digital baseband in the opposite direction (i.e., from distribution hub to headend)

Thus the system provides for full duplex (two-way) video communication.

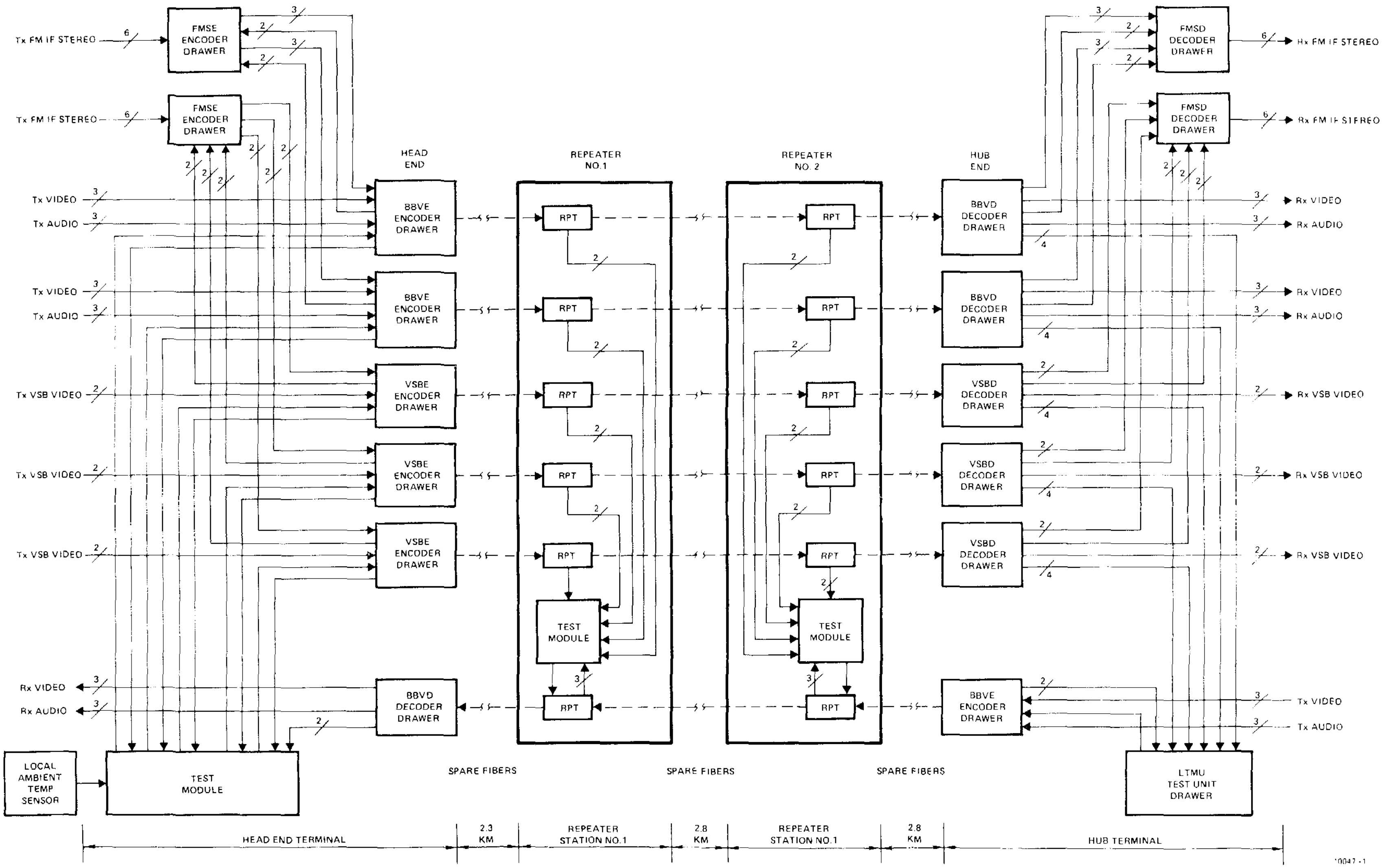

Figure 1. Fiber-Optic Supertrunk Link Block Diagram

The total system length selected for this system is 7.8 km, the distance between the head-end terminal location and the hub distribution location.

A block diagram of the system is shown in Figure 1.

3.1 Baseband TV Processing

In order to transmit studio quality signals, a baseband encoded digital TV signal requires 8 bits sampled at or above the Nyquist rate. The sampling rate was chosen at 10.74 MHz, the third harmonic of the color subcarrier frequency. An additional ninth bit is required for multiplexing the audio portion of the signal and for carrying the frame synchronizing data. A tenth bit is used for a parity bit for error detection and concealment to reduce the effect of bit errors on decoded video quality. With this data format, each single baseband TV signal produces a 107.4 megabit per second (Mb/s) digital bit stream.

Three such digital bit streams are then multiplexed into one serial bit stream at 322.2 Mb/s, which is in turn transmitted over the fiber-optic link. The FM stereo bits are interleaved into the bit stream into spare time-division multiplexed timeslots.

3.2 Vestigal Sideband Processing

The VSB encoded TV signal is encoded in a similar manner to the baseband scheme previously described, but is sampled at a higher sampling rate of 16.1 MHz because of its higher analog bandwidth. The VSB digital data format produces a bit stream at 161.1 Mb/s. Two such bit streams are interleaved into one serial bit stream at 322.2 Mb/s for transmission over the link.

3.3 Fiber-Optic Link

The system uses injection laser diode (ILD) transmitters and avalanche photodiode (APD) receivers at both ends of the link as well as in repeaters.

A block diagram of the ILD transmitter is shown in Figure 2. The transmitter outputs 322 Mb/s NRZ digital code in optical form, giving over 1 mW of optical power into the fiber. An optical feedback circuit controls and stabilizes the laser threshold over temperature and time variations.

The APD receiver is shown in Figure 3. The optical fiber stub terminates on the face of the photodiode, the output of which is amplified by a wideband, high-gain RF amplifier with AGC.

The fiber-optic link was designed to provide an overall end-to-end system BER of better than one error in 10^9 bits (BER $< 10^{-9}$) at a data rate of 322 Mb/s. Actual BER performance has been measured at better than 10^{-10}, which is the limit of the present test equipment.

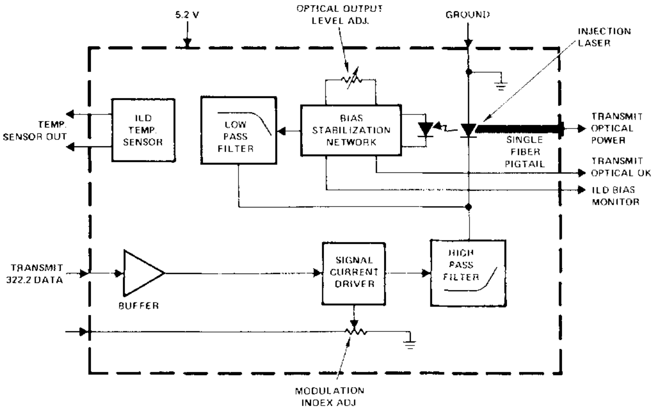

Figure 2. Injection Laser Transmitter 322 Mb/s

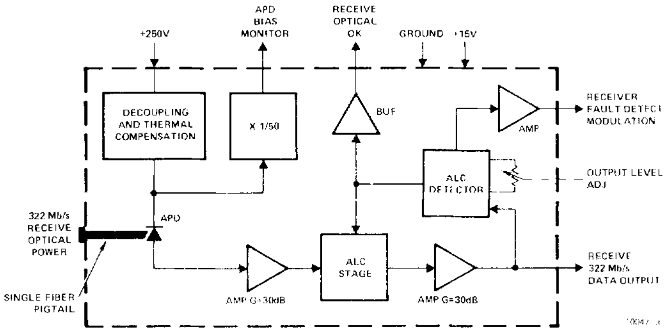

Figure 3. Avalanche Photodiode Receiver, 322 Mb/s

Additional "safety margins" have been incorporated in the system design to ensure that the bit-error rate never limits system performance. For example, a parity detection circuit was designed into the system to search for bit errors in the four most significant bits of the digitized video sample. A logic processor stores the third previous video word to minimize changes in chrominance and luminance coherency, and the current word is checked for parity error. If an error is found, the previous correct sample is used, and the present erroneous sample is discarded. In effect, this technique of error detection and concealment allows errors to be located and removed prior to transmission to system subscribers. The result is a greater improvement in video service quality and reliability.

Another safety feature of the fiber-optic link is optical power margin, or link margin. This is the extra allowance made for equipment aging, variations in optical power, lossy fiber splices, and general time-variant system parameters. The link margin for this supertrunk system is 10 dB, which indicates that a significant optical link degradation can occur over time without the bit-error rate falling below the system BER specification of 10^{-9}.

It might be observed that the system appears to be "overdesigned" for the intended purpose as a CATV supertrunk. Previous work published in the digital video field (by SMPTE and others) has established that a BER of 10^{-7} or less will have no perceptible effect on the quality of the digitally transmitted video. One might next ask why, then, was the system designed for 2 to 3 orders of magnitude better BER performance than required?

The answer lies in the basic need for the CATV industry to accept a more universal view of the tremendous telecommunications potential of fiber optics trunking systems to include other broadband communications services. Data communications, computer and satellite interconnects, two-way telephone trunking, teleconferencing and "wired city" concepts are but a few of the myriad of telecommunications applications effectively addressed by fiber optics. Most of these services are more sensitive to bit-error rate than is digital video, and the specified system BER of 10^{-9} can readily accommodate each of these services.

Some of the excess bit capacity in the system has been specifically dedicated to permit such external synchronous or asynchronous digital data services to be transmitted over the supertrunk link, in addition to the normal video, audio and FM stereo channels. Each Baseband Video Encoder drawer, for example, can accept up to 30 synchronous CVSD [1] voice channels or 10 multiplexed channels of 9600 baud data service modem inputs.

To further illustrate, if one of the six fibers in the cable were dedicated to purely digital telephone trunking, nearly 5,000 standard half-duplex voice channels (Bell-type 64 kb/s logarithmic companded voice) can be accommodated on one single-fiber.

3.4 Computer Simulation Model

An important tool used in the design of the 322 Mb/s digital fiber-optic link was the computer simulation model of the so-called "linear channel" of a repeater-to-repeater span. This model, shown in Figure 4, simulates the effects of the injection laser transmitter, the optical cable delay distortion or dispersion, the photodiode and amplifier, the noise filter and the equalizer on the received waveform prior to reshaping. The output of the computer model is a simulated eye pattern [2] which gives a measure of the quality of the channel. Figure 5a shows the eye diagram for a 2.8 km repeater span and no delay distortion equalization. The effect of a simple equalizer is illustrated in Figure 5b.

A photograph of the actual measured eye pattern over the 2.8 km optical link at 322 Mb/s is shown in Figure 6, confirming the predicted link performance using computer simulation.

The results of the computer simulation are coupled with the known noise characteristics of the receiver to predict the BER as a function of received optical power. Figure 7 gives this relationship for a 3 km repeater span both with and without delay distortion equalization. Further analysis shows that the degradation in BER performance caused by cable dispersion is slightly less than the noise penalty associated with equalization, so that the unequalized receiver is about 0.7 dB more sensitive than the

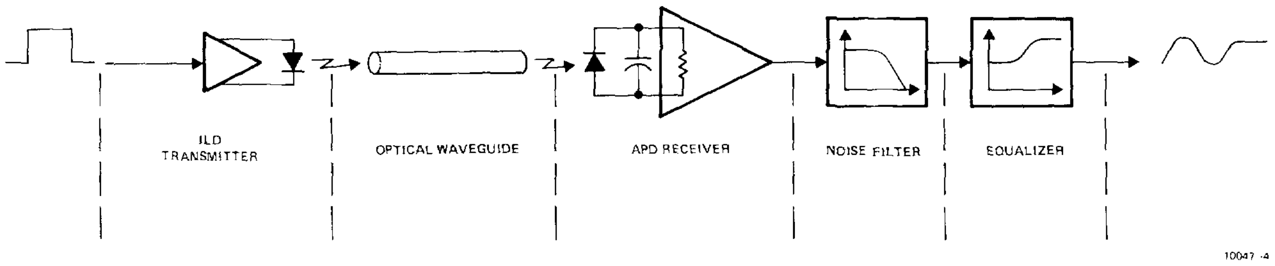

Figure 4. Linear Channel Waveform Simulation Model

[1] CVSD refers to Continuously Variable Slope Delta modulation, a companding method of digital voice modulation used to convert voice signals into serial NRZ digital data, and to reconvert that data into voice. These functions are currently available in single 14-pin CMOS integrated circuits, such as the Harris Semiconductor HC-55532 series.

[2] The eye pattern is an oscilloscope display used as a qualitative indication of the performance of a digital PCM system. The degree of "eye opening" enables one to tell at a glance the effects of bandwidth limiting and noise accumulation in the system. In general, the wider the eye opening, the lower the probability that the receiving equipment will make errors in reading the binary digits of the PCM bit stream.

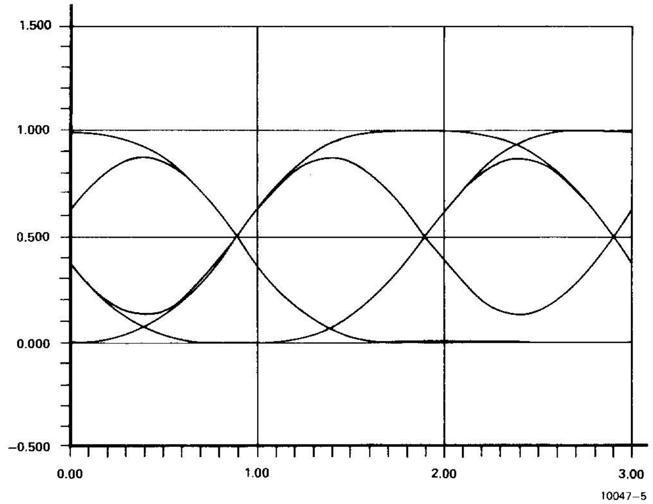

Figure 5a. Simulated Eye Diagram for Unequalized 2.8 km, 322 Mb/s Repeater Span

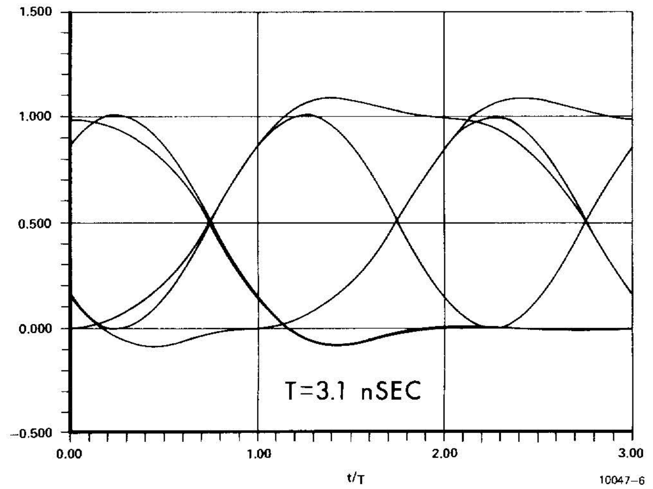

Figure 5b. Simulated Eye Diagram for Equalized 2.8 km, 322 Mb/s Repeater Span

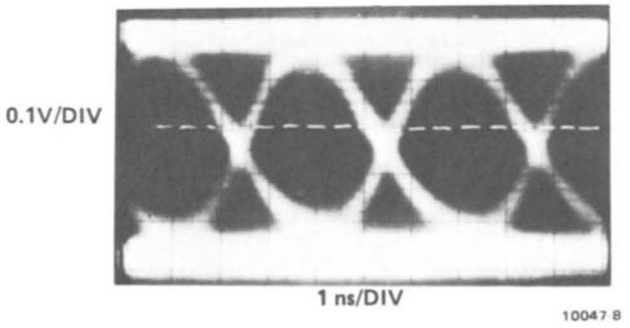

Figure 6. Measured Eye Diagram for Unequalized 2.8 km, 322 Mb/s Repeater Span

equalized receiver. Therefore equalization of the repeater link in this case offered no advantage whatever in performance, and the link contains no equalization circuitry.

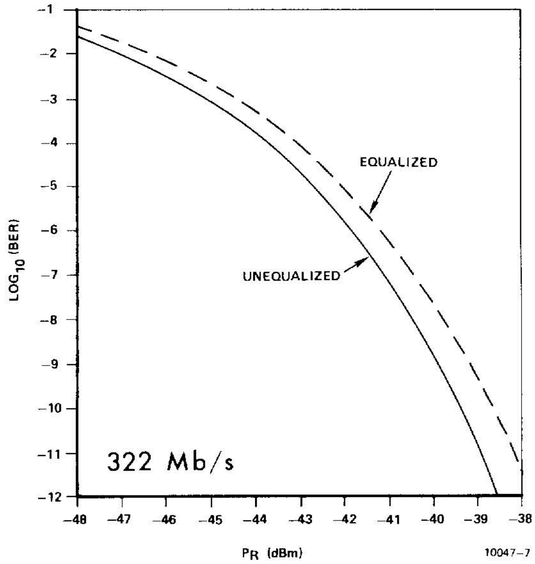

Figure 7. Bit-Error Rate Versus Average Received Optical Power

4.0 AUTOMATIC FAULT DIAGNOSTICS

One of the major objectives in the design of this system was to directly address some of the most challenging operational and maintenance concerns of the CATV industry:

- How does the CATV system operator determine the location and nature of a system failure?
- Is it possible to provide an "early warning" system to the CATV operator, providing in advance, the location, nature and rate of degradation of a system link component?
- Can the means be provided by which both the long- and short-term system performance parameters can be monitored to provide trend data?

Several technical approaches were considered to meet these challenging requirements, ranging from simple manual test sets to computer-controlled automatic test sequencers. The selected approach was incorporated on a medium-complexity, yet cost-effective digital on-line performance monitor called the Link Test and Maintenance Unit (LTMU), which is included as part of the total system equipment configuration.

The LTMU provides meaningful on-line data to the system operator about every important parameter in the system, including bit-error rate, repeater quality and condition and remote temperature conditions.

In comparison to previous CATV system performance monitors, the LTMU represents a quantum jump in the level of system fault diagnostic equipment. Yet in comparison to the technology of the fiber-optic trunking system to be monitored, the LTMU represents a reasoned trade-off between test sophistication and the requirement for a practical tool for system operator personnel.

4.1 Continuous Monitoring

The LTMU continuously monitors the bit-error rate of the digital bit stream at the receiver terminal. An automatic audible alarm is intitiated at the hub terminal location if the system BER exceeds a preset threshold.

In addition to BER monitoring, the LTMU can "call up" any transmitter or receiver module in any fiber-optic repeater unit anywhere in the system, and ask for qualitative status and performance information. This process of digital "interrogation-and-response" to and from the LTMU to other remote system components is the key to rapid fault location and an early warning system of degraded performance.

A transponder module located in every repeater unit enables the LTMU and repeater subassemblies to digitally communicate via unique digital code addresses to each subassembly. Each unit so addressed replies qualitatively as to the condition of the laser transmitter or the photodiode receiver. These data are visually displayed along with BER performance on the LTMU's digital panel readout. The system operator technician simply records these values periodically in a daily log. Thus, any data trends toward degradation will become apparent as variations from given tolerances, and corrective action can be taken before a catastrophic failure occurs and the link goes down. Further, a repair technician can identify from the LTMU the exact repeater, subassembly and module to be replaced before he leaves the shop.

The cost benefits to the system operator in fault location time, troubleshooting, system reliability and customer service complaints are apparent.

5.0 CONCLUSION

This paper has presented a report on the first major CATV installation of fiber optics trunking using digital television transmission. Fiber optics CATV transmission offers both a challenge and a promise: A challenge for the CATV community to adapt and cope with a rapid technological changeover, and the promise of economically providing extended broadband services to outlying or marginally populated market areas not previously considered within reach.

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