A POINT-TO-MULTIPOINT FIBER OPTIC CATV TRANSPORT SYSTEM FOR THE CITY OF CLEVELAND, OHIO

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ABSTRACT

The use of fiber optic analog FM transmission in point-to-point CATV trunking applications is now well established and widespread. Owing to advances in single-mode fiber and device technologies, and the maturing of single-mode optical coupler manufacturing, it is now technically sound and economically attractive to implement point-to-multipoint CATV trunking on fiber in multiheadend/hub systems.

In this paper, we describe the Cleveland, Ohio, multiheadend/hub topology, the pros and cons of analog FM versus digital systems, fiber plant and headend/hub design considerations, and end-to-end performance of the installed system.

This system was manufactured and installed by Catel Telecommunications, Inc., of Fremont, California, for Ohio Bell Telephone (OBT), an AMERITECH company.

INTRODUCTION

The Ohio Bell Telephone Company is constructing a CATV system for the North Coast Cable Company, Ltd., the City of Cleveland CATV franchise operator.

The multichannel fiber optic trunking system and the headend/hubs will be owned, operated, and maintained by OBT. When complete, the CATV system will serve approximately 220,000 dwelling units. The ultimate objective for any CATV system design is to deliver and maintain high quality signals to all subscribers. Today's wide deviation FM-FDM fiber optic transport systems offer virtually transparent transmission of video, audio, and data for distances of more than 20 miles without repeaters.

Point-to-multipoint fiber systems can be configured in "star" or "tree" topologies such that high quality signals are carried deep into population centers, thus avoiding the need for long amplifier cascades in the distribution trunks. This design approach minimizes signal degradation, and enhances network reliability and availability.

The Cleveland system, believed to be the largest multiheadend fiber optic CATV point-to-multipoint system of its kind, was designed with those objectives in mind. It consists of one main headend and six regional headend/hubs (See Figure 1).

The initial design capacity (including future expansion) is for eighty-eight NTSC video channels and BTSC stereo TV or monaural program audio channels, together with thirty-five off-air broadcast FM radio signals, nine RS232C data channels, and an emergency alert control signal to be multiplexed and transmitted downstream on six optical fibers from the main headend to the six regional headend/hubs. In addition, there is sufficient bandwidth left for future new services.

In the upstream direction, up to twelve NTSC video channels and BTSC stereo TV or monaural program audio channels, together with nine RS-232-C data channels, are multiplexed and transmitted on one fiber from the regional headend/hubs to the main headend. In addition, two spare fibers (one for each direction) are available for maintenance purposes. Utilizing wide deviation FM-FDM techniques, similar to satellite video transmission, the Cleveland system offers integrated multiple services with capacity, flexibility, performance, and costs that are beyond the reach of today's digital systems.

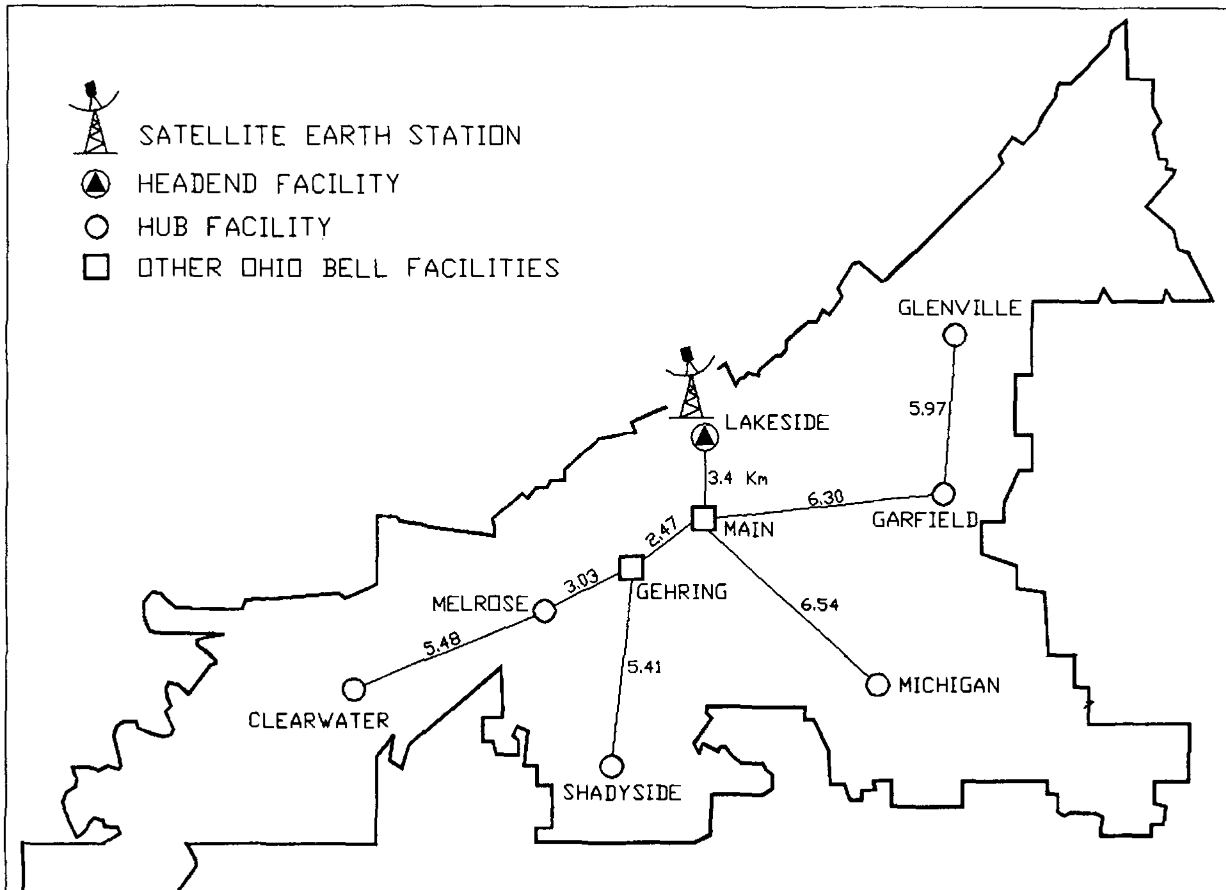

FIGURE 1 : CITY OF CLEVELAND CATV HEADEND AND HUB SITES

ANALOG VERSUS DIGITAL--THE SELECTION PROCESS

Modern CATV trunking systems have evolved into fully developed, integrated, multiple-service networks of high capacity, and great versatility and flexibility. We find that as technology advances and new services are introduced, it becomes necessary to accommodate a wide variety of signals, ranging from complex analog to simple data, on the same network. This must be done economically and without impacting the existing ongoing services. The viability of a given system, be it analog or digital, must therefore be examined with those considerations in mind.

In July 1986, OBT issued a Request for Proposal (RFP) detailing the requirements for the fiber optic system that will be discussed in this paper. Suppliers were requested to submit their proposals on an "engineer, furnish, and install" basis, utilizing their system features to the fullest advantage. All proposed systems, analog and digital alike, were evaluated from both technical and economic standpoints.

The basis for OBT's evaluation, which took place in the latter part of 1986, was the ten-point requirements summarized in Table 1.

Economically, the systems were judged using the "lifecost" analysis, which considers such economic factors as (a) system cost, (b) spare parts, (c) engineering charges, (d) installation charges, (e) software charges, (f) power requirements, (g) test equipment requirements, (h) failure rates, (i) shipping costs, (j) repair costs in and out of warranty, and (k) training costs.

Technical ranking was done on (a) specifications and features per items 1 through 9 of Table 1; and (b) hands-on verification tests that simulate operating conditions similar to the "real-life" system. The results of OBT's evaluation (see Table 1) indicate that on eight counts out of ten, analog

FM is the preferred choice over digital.

Undoubtedly, the future of telecommunications is with digital, and it will eventually prevail. However, digital CATV transport systems will only become viable when a total system design approach is undertaken, agreed standards are adopted, and cost becomes competitive.

Table 1 -- OHIO BELL EVALUATION, DIGITAL VERSUS ANALOG

Item	Requirements	Choice	Comments
1.	Maximum channel capacity	Analog	16 video ch/fiber analog; 8 video ch/fiber digital with 565 MB/S bit rate
2.	RS-250-B medium-haul or better	Analog	Video SNR better than 65 dB analog and 60 dB digital with 8-bit encoding and DPCM
3.	Accommodate BTSC format stereo or monaural audio	Analog	Digital could not handle signal format
4.	Accommodate broadcast FM radio channels	Analog	Digital could not handle signal format
5.	Accommodate bidirectional RS-232-C	Analog	Digital requires either individual fibers from each hub to headend for upstream data or "drop and insert" repeaters
6.	Controls, monitors, and alarms for maintenance	Digital	Digital is inherently easier to troubleshoot and maintain, compared to analog
7.	Upgrading flexibility	Analog	Digital is rigid and inflexible to upgrades; analog FDM is inherently flexible to upgrades
8.	Distances per Fig. 1	Either	Analog can span ≈25 miles without repeaters; the advantage of digital is in long-hauls of over 50 miles, where signals can be regenerated without loss of quality
9.	Accommodate upstream transmission	Analog	Same as 5
10.	Minimum "lifecost" for complete system	Analog	Digital systems are currently more costly

MULTIHEAD/HUB TOPOLOGY

As a provider of local telephone service to the City of Cleveland, Ohio Bell has had a unique advantage in selecting the optimum locations for the CATV headend and hubs. Naturally, they were placed in the telephone central offices, which are strategically located in the population centers throughout the city. Figure 1 depicts the city map, and the location of the satellite earth station and main headend facility (at Lakeside), as well as the six hubs in the telephone central offices (at Clearwater, Melrose, Shadyside, Michigan, Garfield, and Glenville).

The satellite earth station and the equipment associated with the signal feeds are owned, operated, and maintained by North Coast Cable Company. The signals that feed the entire CATV system (except upstream transmission) come from the North Coast Lakeside facility in the same building as the main headend.

At the time of activation in December 1987, there were thirty-seven C-band satellite TV receive signals, ten off-air TV channels, thirteen locally generated TV signals, thirty-five processed broadcast FM radio channels, and an emergency alert control signal. Nine additional bidirectional data channels were provided for monitoring and control of modulators, encoders, and trunk amplifiers. There were also four video and audio channels for transmission from each hub to the main headend.

In any system of this size and complexity, there are numerous feasible configurations of both fiber routing and channel loading. The following criteria were considered to determine those parameters:

- Maximize reliability and system availability.
- Provide an all-passive fiber plant.
- Minimize the number of fibers per cable, the number of cables, and the total system fiber kilometers.
- Minimize the number of fiber splices.
- Provide equal optical signal power at all hubs.
- Maximize expansion capabilities for both channel capacity and additional new services.
- Provide a virtually transparent point-to-multipoint transport system.
- Maximize system loss margin.
- Minimize "lifecost."

Figure 2 shows the chosen link topology, which is identical for both downstream and upstream transmission. The network consists of two FM trunks, east and west of Lakeside. The west trunk services the Clearwater, Melrose, and Shadyside hubs; the east trunk services the Glenville, Garfield, and Michigan hubs. Optical couplers are installed at the main facility to

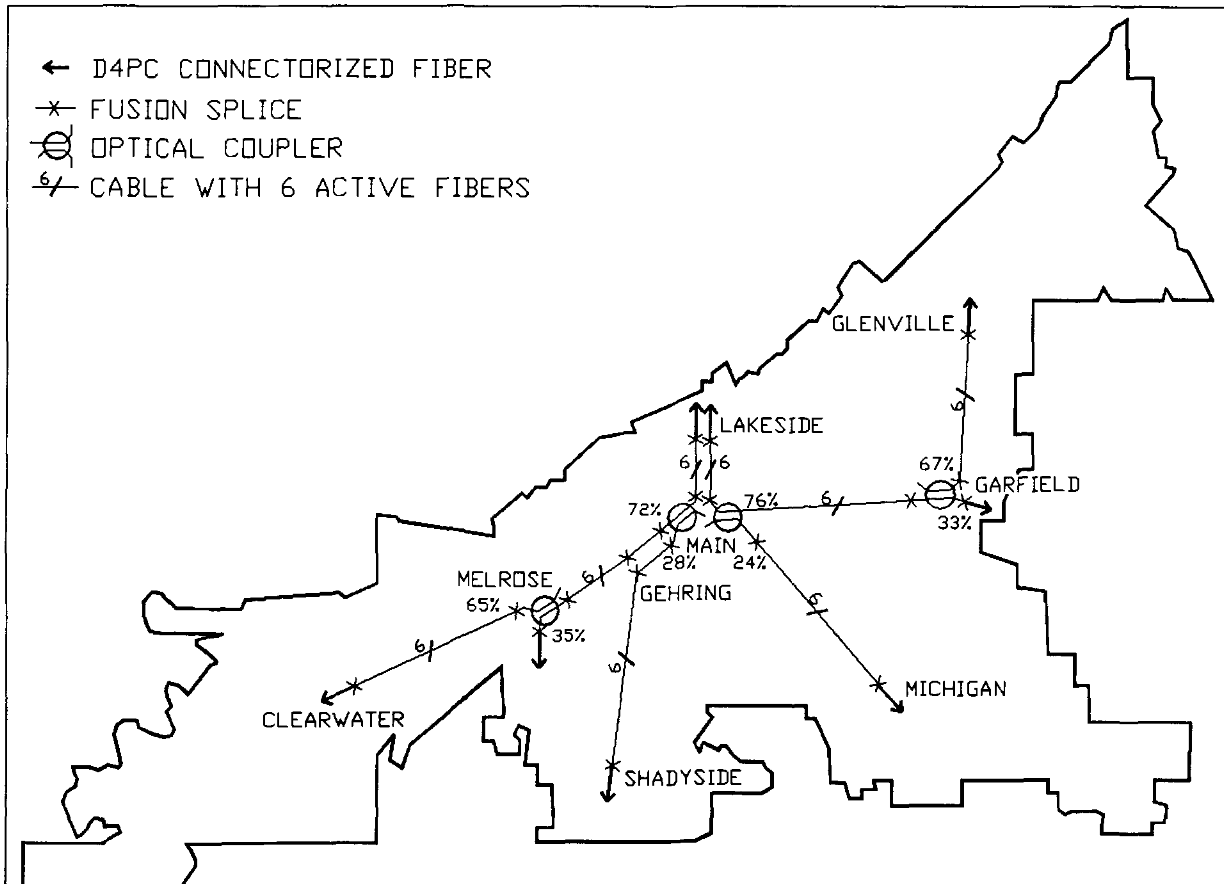

FIGURE 2 : CITY OF CLEVELAND CATV FIBER OPTIC PLANT

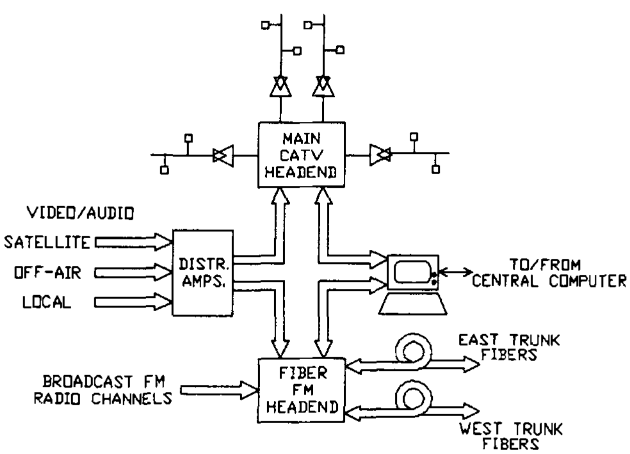

FIGURE 3 : MAIN HEADEND SYSTEM CONFIGURATION

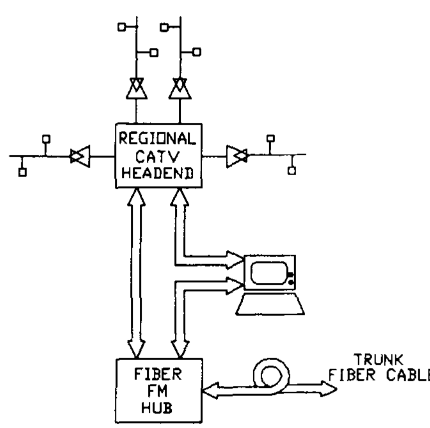

FIGURE 4 : REGIONAL HEADEND/HUB SYSTEM CONFIGURATION

split/combine the signals for transmission to and from the east and west hubs. Additional optical couplers are used at Garfield and Melrose to provide further signal splitting/combining to and from the remaining hubs.

Initially, there are six active fibers for each of the east and west trunks. Five are for downstream transmission, and one is for upstream transmission. Each fiber can carry a minimum of fourteen video and audio channels, as well as other services such as broadband (Ethernet) LAN, T1, T2, orderwire, telemetry, and so forth.

Figures 3 and 4 depict the main headend and regional headend/hub system configurations, respectively.

FIBER PLANT DESIGN

In general, the fiber plant design must meet both bandwidth and loss requirements of the system. The electrical bandwidth BW of the laser/fiber combination for a single-mode fiber is given by (1).

$$BW = \frac{0.187}{D \times \Delta\lambda \times L} \qquad (1)$$

where

D is the total (chromatic plus waveguide) fiber dispersion in ps/nm and km

$\Delta\lambda$ is the RMS (root mean square) value of the laser diode spectrum in nm and

L is the length of the fiber in km.

An InGaAsP Fabry-Perot laser has a typical $\Delta\lambda$ of 3 nm, and the fiber dispersion in a ±10 nm window around 1300 nm is from 0 to 3 ps/nm x km. A worst-case design must account for spread in laser center wavelength from unit to unit, as well as long-term wavelength drift due to aging. Conservatively, we will assume a wavelength shift of 10 nm, resulting in a maximum dispersion of 3 ps/nm x km and a calculated bandwidth distance product of 21 GHz x km. The longest link in our system is approximately 15 km; the minimum available bandwidth is therefore 1.5 GHz. Since the required system bandwidth is 550 MHz, the fiber link bandwidth is clearly not a limiting factor.

Next, we will address fiber plant loss and the system loss budget. Total fiber plant loss A_T in dB is given by (2).

$$A_T = A_F + A_S + A_{CR} + A_{EL} + A_C \qquad (2)$$

where

A_F is total fiber loss

A_S is loss due to splices

A_{CR} is loss of optical couplers due to coupling ratios

A_{EL} is excess loss of the optical coupler and

A_C is loss due to optical connectors.

The fiber plant parameters and loss data in Table 2 are based on the following assumptions:

(1) Maximum fiber attenuation at 1300 nm is 0.5 dB/km.

(2) Maximum splice (fusion) loss is 0.2 dB.

Table 2 -- FIBER PLANT DATA

	LAKESIDE TO					
Parameter	MCHGN	GRFLD	GLNVL	SHDSD	MLRS	CLWTR
Distance (km)	9.94	9.70	15.67	11.28	8.90	14.38
Fiber Loss A_F (dB)	4.97	4.85	7.85	5.64	4.45	7.19
Main Couplers CR (%)	24.00	76.00	76.00	28.00	72.00	72.00
Main Couplers A_{CR} (dB)	6.20	1.20	1.20	5.53	1.43	1.43
Melrose Coupler CR (%)	--	--	--	--	35.00	65.00
Melrose Coupler A_{CR} (dB)	--	--	--	--	4.56	1.87
Garfield Coupler CR (%)	--	33.00	67.00	--	--	--
Garfield Coupler A_{CR} (dB)	--	4.81	1.74	--	--	--
Couplers EL (dB)	0.10	0.20	0.20	0.10	0.20	0.20
Splice Losses A_S (dB)	0.80	1.20	1.20	0.80	1.20	1.20
Connector Losses A_C (dB)	1.00	1.00	1.00	1.00	1.00	1.00
Total Loss A_T (dB)	13.07	13.26	13.19	13.27	13.04	13.09
Measured Average Loss A_{TM} (dB)	10.60	10.60	10.40	10.90	10.40	10.50
Measured Maximum Loss A_{MAX} (dB)	11.00	10.90	10.80	11.10	10.80	10.90
Measured Minimum Loss A_{MIN} (dB)	10.20	10.00	10.00	10.40	9.90	10.10

(3) Couplers are fusion spliced directly to the fiber cable.

(4) Excess loss of couplers is 0.1 dB.

(5) Connector loss allowance is 0.5 dB.

To equalize the path losses, the coupling ration CR is calculated from Equation (3).

$$CR = \frac{10^{\frac{\Delta A}{10}}}{1 + 10^{\frac{\Delta A}{10}}} \qquad (3)$$

where ΔA is the dB difference in the path losses.

From Table 2 we observe that, indeed, total loss A_T from headend to each hub is equalized with less than 0.5 dB. Also, measured average loss A_{TM} of the link is consistently lower than calculated loss by approximately 2.5 dB, which is typical for worst-case designs. These lower losses are attributed mainly to lower fiber loss and lower splice and connector losses achieved by careful selection of components and high quality installation. To avoid losses due to dissimilar fibers, the pigtails, patchcords, and couplers were made of the same type of fiber as the cable. The cable was pulled in long sections without intermediate splices, except for one at the Gehring facility. The optical connectors used are a physical contact (PC) type, which were chosen to minimize back reflections. For the same reason, fusion splicing was used rather than mechanical splices.

SYSTEM LOSS BUDGET

The system loss budget can now be determined from Figure 5, which depicts the weighted video signal-to-noise ratio (SNRw) as a function of received optical power/transmission distance for sixteen channels per fiber loading and 4-MHz deviation, with sync tip to peak white (STPW) preemphasized video. The data in Figure 5 was obtained experimentally, by measuring several transmitter-receiver pairs. Typically, there is a 2- to 3-dB difference in SNRw between the best and the worst channel. For the purpose of the loss budget calculation (see Table 3), we have used the worst-channel data and the 60-dB SNRw as a minimum requirement. The resulting system gain is 20 dB with 2 dB of allocated margin, and a remaining unallocated system margin of 6.7 dB minimum for a total of 8.7 dB calculated system margin. The actual installed system margin is 10.7 dB minimum, and the operating region is on the flat part of the SNRw curve.

The flat SNRw section of Figure 5 is characterized by the relative intensity noise (RIN) of the link, which includes the laser, the fiber plant, and the detector. In this region, the performance of the system is maximized, and typically meets RS-250-B short-haul requirements. To realize this very

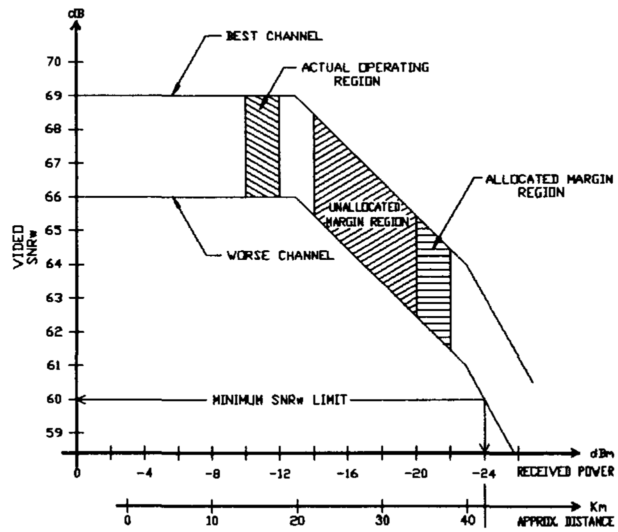

FIGURE 5 - VIDEO SNRw VERSUS RECEIVED POWER

Table 3 -- SYSTEM LOSS BUDGET

A.	Transmitter output power (min)	-2.0 dBm
B.	Receiver input power (min)	-24.0 dBm
C.	System gain (A-B)	22.0 dBm
D.	Allocated Margin for Equipment (temperature, aging, etc.)	1.0 dB
E.	Allocated margin for fiber plant (splices, connectors, etc.)	1.0 dB
F.	Total allocated margin (D+E)	2.0 dB
G.	System gain with allocated margin (C-F)	20.0 dB
H.	Total Loss A_T from Table 2	13.3 dB
I.	Unallocated system margin (G-H)	6.7 dB
J.	Measured maximum loss A_{MAX} from Table 2	11.1 dB
K.	Unallocated actual system margin (G-I)	8.9 dB
L.	Total calculated system margin (F+I)	8.7 dB
M.	Total actual system margin (F+K)	10.7 dB

high system performance, one must choose a laser that is relatively insensitive to back reflections, and has low RIN and mode partitioning noise characteristics. Furthermore, the back reflection from splices, connectors, and the fiber-to-detector interface should be minmized.

HEADEND/HUB DESIGN

The fiber/FM headend and hub diagrams are shown in Figures 6 and 7, respectively. The system was initially equipped with five groups of twelve video/audio channels per fiber, for a total of sixty channels. The thirty-five broadcast FM radio channels are processed (frequency translated and RF level equalized) and transmitted on fiber number one, together with their video/audio channels. The frequency plan for downstream transmission is shown in Figure 8A. Spacing between the video/audio channels is 34 MHz, and 400 kHz between the FM channels. All video input and output signals are NTSC baseband nonscrambled. The audio interfaces are at 4.5 MHz with either BTSC stereo TV or monaural formats. In order to preserve the high quality (SNR, separation, etc.) of both the video and the audio, the 4.5 MHz audio is frequency doubled before it is combined with the video baseband signal. This results in twice the deviation and a 6-dB SNR improvement, negligable crosstalk between video and audio (and vice versa), and the means to easily separate the video and audio at the receive sites.

The composite video/9-MHz audio signal feeds a low phase-noise linear FM modulator. The deviation (adjustable) was set to 4 MHz STPW, which is the best compromise between channel spacing and SNR. Frequency agile converters (adjustable in 1-MHz increments) and passive RF combiners provide frequency division multiplexing (FDM) to the RF carriers. The combined FM-FDM signal is split into two identical signals, which feed the east and west trunk optical transmitters.

Frequency shift keying (FSK) data modems are used to transmit the nine RS-232-C data channels and the emergency alert control signal on fiber number two, together with the second group of twelve video/audio channels. Currently, fibers three, four, and five carry twelve video/audio channels each. In the upstream direction, the signals from three transmitters are optically combined on one fiber for each east and west trunk. The frequency plan for the

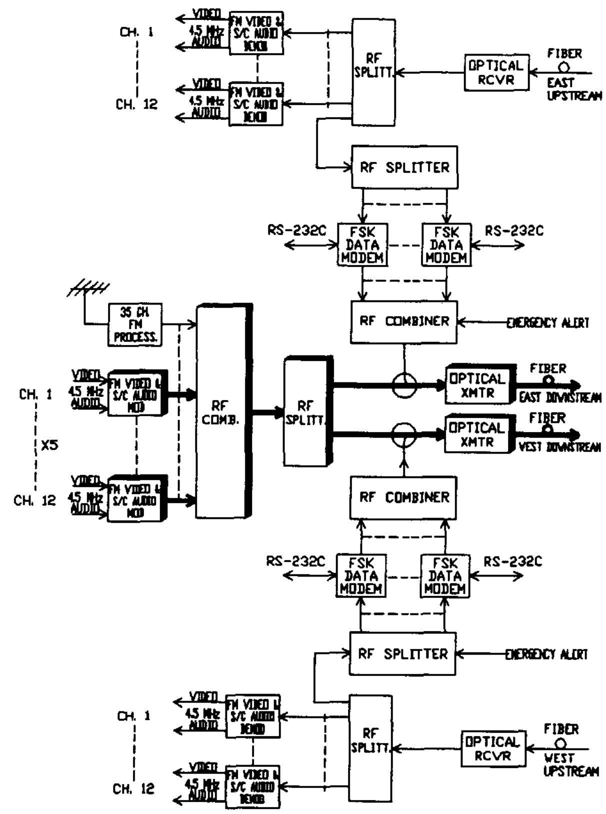

FIGURE 6 : FIBER/FM HEADEND

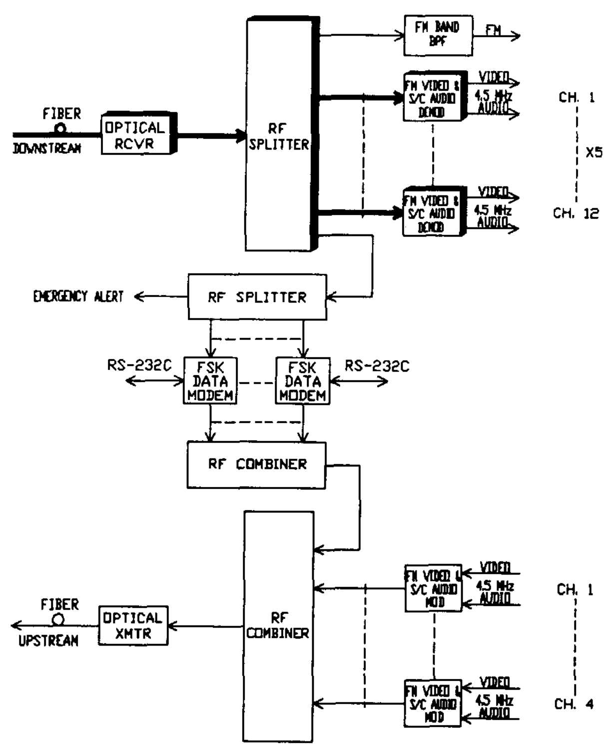

FIGURE 7 : FIBER/FM HUB

upstream transmission is depicted in Figure 8B. All six hub sites are identical in design; each receives all the channels from the headend and transmits four video/audio channels and three RS-232-C data channels

The 5 to 40 MHz band is reserved for future new services such as orderwire, T1 or T2, broadband LAN, and alarm remoting. The optical transmitters/receivers and the FM modulators/demodulators provide the alarm outputs that can be transmitted to the main headend via the upstream fiber link.

NOTES:
1. FM IS TRANSMITTED ON FIBER No. 1 ONLY.
2. DATA IS TRANSMITTED ON FIBER No. 2 (DOWNSTREAM) AND No. 6 (UPSTREAM).
3. AUDIO IS TRANSMITTED ON 9 MHz SUBCARRIER ABOVE VIDEO.

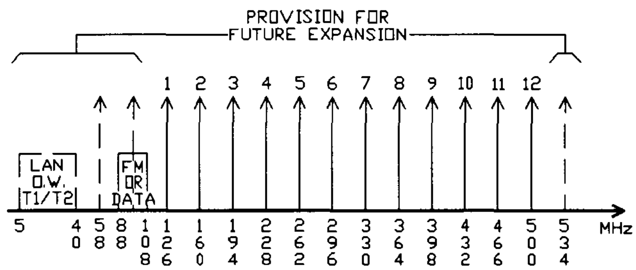

FIGURE 8A : FREQUENCY PLAN DOWNSTREAM

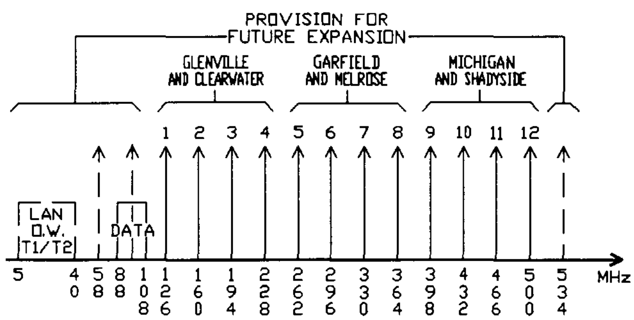

FIGURE 8B : FREQUENCY PLAN UPSTREAM

SYSTEM PERFORMANCE

The Cleveland system was designed to provide near short-haul EIA RS-250-B performance, and a guaranteed medium-haul performance. Back-to-back (without the fiber optics), the video SNR_W is in excess of 73 dB. The video/audio parameters (except SNR) are not affected by the broadband fiber link which is virtually transparent to frequency modulated signals. The only degradation mechanisms are additive broadband and intermodulation noise. The advantage of wide deviation FM is in its immunity to broadband and intermodulation noise. The video SNR_W is given by (4).

$$SNR_W = K + CNR + 10\log\frac{B_{IF}}{B_F} + 20\log\frac{1.6\,\Delta F}{B_F} \qquad (4)$$

where

- K is constant (≈23.7 dB) made of weighting network, deemphasis, and rms to p-p conversion factors
- CNR is carrier-to-noise radio in the IF bandwidth
- B_{IF} is IF bandwidth
- B_F is baseband filter bandwidth and
- ΔF is sync tip to peak white (STPW) deviation.

With ΔF = 4 MHz, B_{IF} = 30 MHz and B_F = 5 MHz, the SNR_W is improved by approximately 34 dB above CNR.

The end-to-end performance of a typical video/audio channel is shown in Table 4. The short-haul specifications are included for comparison purposes. The histograms of the video SNR_W are included in Figure 9.

Table 4 -- CLEVELAND F/O TRANSPORT SYSTEM TYPICAL END-TO-END PERFORMANCE

	Parameter	Requirement	Measured Value	Short-Haul
NTSC Video	Multiburst 0.5	≤±0.25 dB	0.0 dB	≤±0.10 dB
	Multiburst 1.0	≤±0.35 dB	-0.2 dB	≤±0.15 dB
	Multiburst 2.0	≤±0.50 dB	-0.3 dB	<±0.15 dB
	Multiburst 3.0	≤±0.60 dB	-0.1 dB	<±0.20 dB
	Multiburst 3.58	≤±0.35 dB	0.1 dB	<±0.10 dB
	Multiburst 4.2	≤±0.60 dB	0.4 dB	<±0.20 dB
	C/L Gain	≤± 4.0 IRE	1.0 IRE	≤± 1.0 IRE
	C/L Delay	≤±33.0 nsec	10.0 nsec	≤±20.0 nsec
	DIFF Gain	≤ 5.0%	0.57%	≤2.0%
	DIFF Phase	≤±1.3°	0.46°	≤0.5°
	Field Time	≤3.0 IRE	1.0 IRE	≤3.0 IRE
	Line Time	≤1.0 IRE	0.4 IRE	≤0.5 IRE
	Short Time	≤4.0 IRE	2.8 IRE	≤4.0 IRE
	Long Time	≤8.0 IRE	1.0 IRE	≤8.0 IRE
	C/L Intermod	≤2.0%	-0.4%	≤1.0°
	C Nonlinear Gain	≤2.0%	0.0%	≤1.0%
	C Nonlinear Phase	<2.0°	0.0°	≤1.0°
	S/N Weighted	≥60.0 dB	67.7 dB	>67.0 dB
Audio	THD	≤ 1.0%	0.2%	≤1.0%
	S/N	>65.0 dB	67.0 dB	>66.0 dB

In conclusion, the Cleveland system fully meets, and in most cases exceeds, the design requirements and performance expectations.

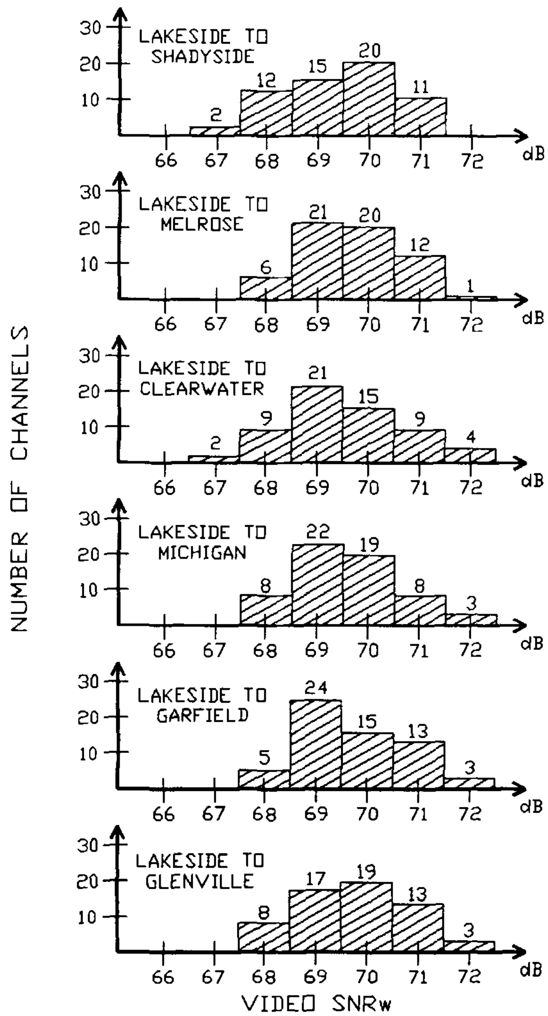

FIGURE 9 : VIDEO SNRw HISTOGRAMS