Fiber Optics Broadband Systems Present and Future

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1. Introduction

In the search for an optimal system for CATV broadband networks ,certain key objectives to be met include:

a)Achievement of highest quality of the delivered video, audio or data
b) Reduced or no sensitivity to EMI, crosstalk etc.
c) No adverse environmental effects
d) Low equipment and installation cost
e) Low system maintenance cost
f) Information security

Degradations in a typical CATV system are caused by the cable itself and the associated repeater amplifiers. They limit the number and the level of the transmitted carriers and the plant bandwidth. As a result, the performance of the signals delivered to the farthest subscriber suffers. Other limitations include :

I) FCC-dictated frequency allocation aimed at minimizing the interference between signals.
II)The system susceptibility to external noise and interference.

For broadband supertrunking signal transportation it is imperative to be able to deliver video **transparently** (with virtually no system-added degradation) from geographically separated locations to distant (tens of miles away) head-ends. Typical CATV delivery systems having repeater amplifiers every 1/2 mile cannot achieve this goal.

Some of approaches that can be used to achieve higher quality of delivered signals include use of microwave links, different modulation over a coaxial cable ,or both. One of the earliest approaches used by Catel was to use FM instead of VSB-AM over coaxial cable or microwave links, with excellent performance results achieved.

With the rapid development of cost - effective optical sources and fiber technology, an attractive and economical approach to the delivery of high quality signals would be to use fiber optics links as transmission media. It would allow the system designer to take full advantage of the wide bandwidth available and of the insensitivity to EMI. Also, no repeaters are required for fiber links less than 25 miles.

2. Why bother with fiber optic - based supertrunks?

The necessity for transparent transmission of video in supertrunks demands that the delivery system performance be extremely high - the performance specifications typically require that the overall video transmission system must meet or exceed the RS250B broadcast industry standards for short or medium haul video transmission .To satisfy these stringent performance requirments **economically,** a careful system design is needed.

The topology of a supertrunk include path lengths extending from several miles to several tents of miles with one or more branches along the way.The number of video channels and their associated audio channels that each supertrunk is required to carry can vary - (depending on the SNR required and the path lengh) - with maximum achievable (using wide deviation FM) being 16.

Coaxial cable - based supertrunks must use booster amplifiers in order to maintain the proper signal levels and CNR in all of the path sections. Although the coaxial cable itself has a wide bandwidth, the booster amplifiers bandwidth is limited to 500 - 600 Mhz. To guarrantee that after a cascade of booster amplifiers the required SNR can be maintained at the farthest receiver location , FM modulation is frequently selected . With the proper modulation index chosen for optimum SNR improvement vs bandwidth expansion , large improvements factors can be achieved at the expense of the number of channels the system can support. If more channels would need to be added either now or in the future, more cables (and booster amplifiers) will be required and the system cost would tend to increase due to the added cost of the cable, additional amplifiers and the maintenance involved.

Microwave supertrunks use Frequency-Division Multiplex methods to combine several FM - modulated video and audio carriers. The combined carriers (typically occupying up to 550 Mhz of bandwidth) are then upconverted and transmitted at microwave frequencies. Although the microwave equipment costs more ,it requires a licenced frequencies to operate and tends to suffer from fading, but it is indispensible whenever it is very difficult or imposible to use a wired system.

Fiber optic supertrunk delivery system offer wide bandwidth, low losses, very small size and weight (and therefore many fibers can be packed into a small space), security of communications and rapidly dropping cost. Because of these properties the system designer can select the frequency plan ,the modulation method and the number of fiber links offering the best and the most economical way of packing the number of required channels into a fiber optic - based supertrunking system.

For long haul paths especially, the benefits derived from a broadband fiber optic supertrunk delivery system can be substantial - both in up front cost as well as in maintenance. Because FM modulation can offer large SNR improvement factors and the bandwidth expansion associated with it can easily and inexpensively be accomodated in a fiber optic link, a broadband fiber optic supertrunk can carry a large number of high quality video channels inexpensively.

3. Elements of an optical fiber broadband system

A block diagram shown in Fig. 1 illustrates the basic components of a fiber optic - based supertrunk. It consists of an RF and a fiber optic subsystem portions and a broadband single mode fiber serving as the transmission medium.

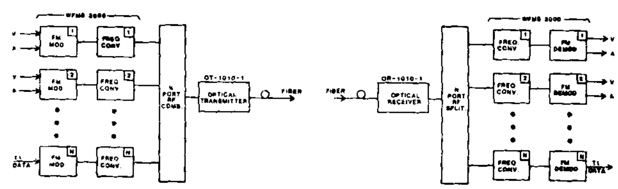

Figure 1: Block diagram of a fiber optic supertrunking system

4. Fiber medium

An optical fiber is a dielectric waveguide that operates at optical frequencies. It is cylindrical in form and it confines the electromagnetic energy in the form of light to within its surfaces and guides the light in a direction parallel to its axis.

One of the principle optical fiber characteristics is its attenuation as a function of wavelength.Three bands which have minimum attenuation to light signals are shown in Figure 2.

Early applications have made exclusive utilization of the 800-900 nm wavelength band , since the fibers made at this time exibited a local minimum in the attenuation curve and optical sources and photodetectors operating at these wavelenghts were available.

Improvement in the fabrications processes by

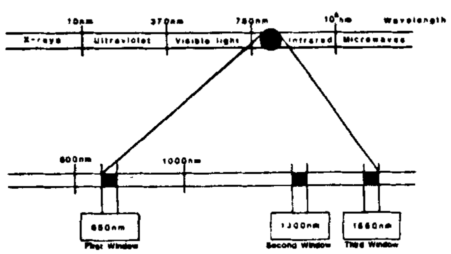

Figure 2: Fiber optics communications windows

the fiber manufacturers have permitted them to produce optical waveguides with very low losses in the 1100 - 1600 nm region (this spectral wavelength band is referred to as the long-wavelength region). Since the 1300 nm wavelength region presents minimum signal dispersion to signals in pure silica fibers, it has been widely used as the choice wavelength in present day uses of single mode fibers

The transmission properties of an optical waveguide are dictated by its structural characteristics. The structure basically establishes the information-carring capacity of the fiber and its environmental response.

The most widely accepted structure of an optical waveguide is the single solid dielectric cylinder of radius a and index of refraction n_1 - this is known as the core of the fiber. The core is surrounded by a solid dielectric known as the cladding having a refractive index n_2 which is less than n_1 .The cladding facilitates the total light reflection into the core, it adds mechanical strength to the fiber and protects the core from surface contaminants.

Variation in the material composition of the core give rise to two commonly used fiber types shown in Figure 3.

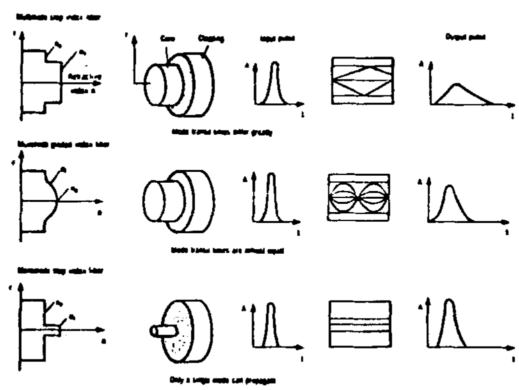

Figure 3: Fiber types and mode of operations

In the first case the refractive index of the core is uniform and undergoes an abrubt change (step) at the cladding boundary. This is called a step-index fiber. In the second case the core index is made to vary as a function of the radial distance from the center - this is known as a graded-index fiber.

Both the step and the graded-index fibers can further be divided into single mode and multimode classes. As the name implies, a single mode sustains only one mode of wave propagation, whereas multimode fibers support many hundreds of modes.

Since multimode fibers have larger core radius, it is easier to launch optical power into the fiber and to interconnect similar fibers. Another advantage is that light can be launched into the multimode fiber using a LED source.

A disadvantage of multimode fibers is that they suffer from internal dispertion. When an optical pulse is launched into the fiber, the optical power in the pulse is distributed over most or all modes of propagations that the fiber supports. Each of the modes propagating through the fiber travels at a slightly different velocity, causing the signal to spread out in time as it travels along the fiber. This is called modal dispersion.

A measure of the information capacity of an optical waveguide is usuallly specified by the bandwidth-distance product in Ghz . Km.

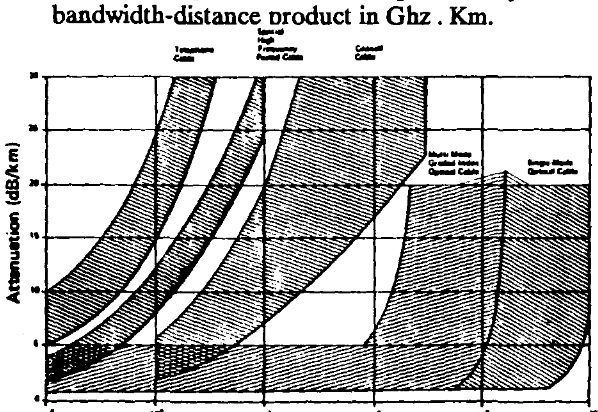

Figure 4: Frequency characteristics of different media

Since intermodal dispersion effects are not present in single mode fibers, they can have very wide signal bandwidths transmission capabilities.

Figure 4 compares the attenuation vs frequency of various media (telephine cable, coaxial cables and different fiber types). It can be determined from the curves that single mode fiber bandwidths exceed 10 Ghz . Km.

5. Optical sources

The principle light sources used for fiber optic communication applications are the laser diodes and light-emmiting diodes (LED). These devices are suitable for fiber transmission systems because they haves adequate output power for wide range of applications, they can be directly modulated by varying the input current to the device, they can have high efficiency and their dimentional characteristics are compatible with those of the optical fiber.

A major difference between LED's and laser diodes is that the optical output from an LED is incoherent , whereas the laser diode output is coherent.

Laser sources generate the optical energy in an optical cavity. The resulting output is highly monochromatic (single wavelength) and the light beam is very directional. (the output has high spatial and temporal coherency). The emmision spectrum of the lasers is narrow (typically 4 nm), they have modulation capabilities of up to 1 Ghz and their radiance is high (1 - 2 mw coupled into the fiber).

In an incoherent LED source no optical cavity exists for wavelength selectivity and the output radiation has a broad spectral width (typically 50 nm) and has modulation capabilities up to 200 Mhz.. In addition, the incoherent optical energy is emitted into the hemisphere according to a cosine power distribution and has a large beam divergence.

The spatially directed coherent optical output from a laser diode can be coupled into either a single mode or multimode fibers. However, sufficiently large incoherent optical power for it to be useful (10 - 50 μw) from an LED can only be coupled into multimode fibers.

Figure 5 shows the effect of resultant fiber optic plant bandwidth as a function of the light source spectral width. It can be seen that very wide bandwidths are possible if a precise control over the optical source spectral width and wavelength can be effectively accomplished.

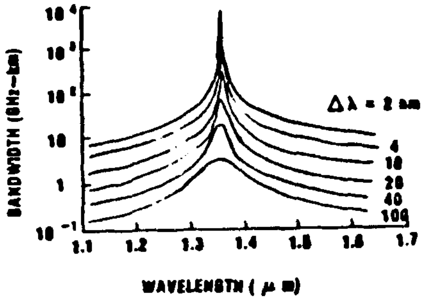

Figure 5: Effect of source spectral width and wavelength deviations

An important factor to consider in the application of laser diodes is the temperature dependence of the threshold current as shown in Figure 6. Consequently, if a constant optical power and undistorted signal outputs is to be

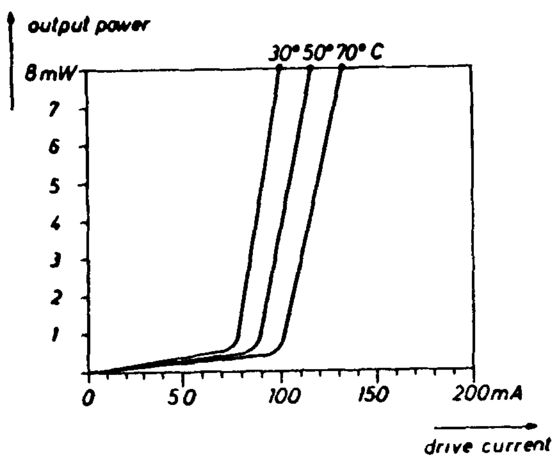

Figure 6: Effects of temperature on lasers

maintained with time, it is necessary to use precise dc bias and temperature control techniques.

For broadband supertrunking applications, intensity modulation of the laser diodes is carried out by making the its drive current above threshold vary about the bias point in proportion to the modulation signal. as shown in Figure 7.

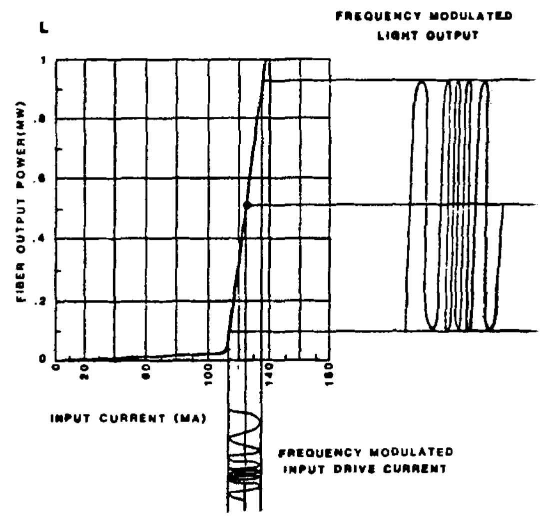

Figure 7: Linear modulation of a laser diode

A requirment for this modulation scheme is that a linear region exist between the light output and the current input. Signal degradations resulting from the nonlenearities in the transfer characteristic of the laser diodes make the implementation of the analog intensity modulation susseptible to both intermodulation and cross-modulation effects if not accounted for.

Methods of compensation for the nonlenearity of the optical sources include different linearization techniques (complementary distortion, negative feedback quasi-feedforword compensations) or use of modulation schemes less sensitive to those distortions such as PPM or wide deviation FM.

6. Optical detectors.

At the receiving end of an optical transmission line there must be a receiving device which interprets the information contained in the optical signal. The first element of this receiver is a photodetector.

Of the semiconductor-based photodetectors, the photodiode is used almost exclusively for fiber optic systems. The two types of photodiodes used are the PIN photodetector and the avalanche photodiode (APD).

The PIN photodiode generates electrical surrent in response to incident light. Two important characteristics of a photodiode are its quantum efficiency and its response speed.

The quantum efficiency η can be defined as

$$\eta = \frac{Ip/q}{Po/h\nu} \qquad (1)$$

Here Ip is the average photocurrent generated by a steady-state average optical power Po incident on the photodetector, q is the electron charge and $h\nu$ is the photon energy.

In practice, 100 photons will create between 30 and 95 electron-hole pairs ,thus yeilding quantum efficiency ranging from 30 to 95%.

The performance of a photodiode is often characterized by its responsivity R. This is related to the quantum efficiency by

$$R = \frac{Ip}{Po} \qquad (2)$$

This parameter is quite useful since it specifies the photocurrent generated per unit optical power.

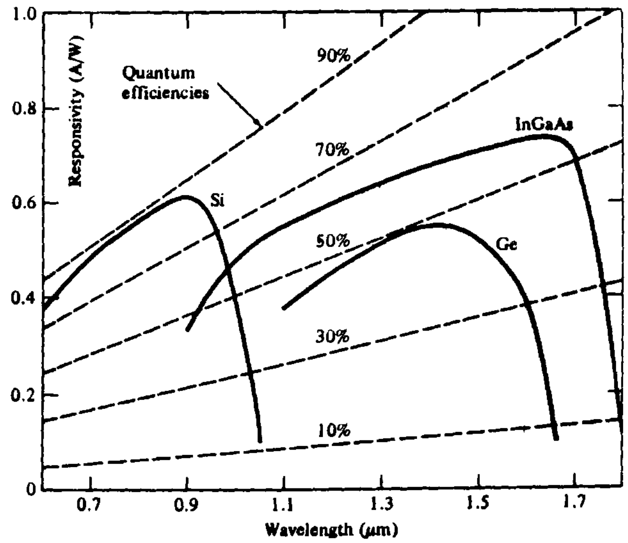

Figure 8: Responsivities of typical detectors

Typical PIN photodiode responsivities as a function of the wavelength can be seen in Figure 8.

PIN diodes are simple to use and they have low dark currents. However, the PIN diode receivers have low sensitivity and low dynamic range too.

The Avalanche photodiode (APD) internally multiplies the primary photocurrent before it enters the input circuitry of the following amplifier.This increases the receiver sensitivitiy since the photocurrent is multiplied before encountering the thermal noise associated with the receiver circuitry. In order for current multiplication to take place, the photogenerated carriers must traverse a region where very high elelctric field is present. The photogenerated electrons can now gain enough energy to ionize forward bound electrons before colliding with them. The newly created carriers are also accelerated by the high electric field ,thus gaining enough energy to cause further impact ionization. This phenomena is the avalanche effect.

The APD's require high bias voltages (Si - 300V, Ge - 30 V), the multiplication factors are statistical and can be temperature-dependent. APD devices also tend to have high dark currents and excess noise for long wavelength devices. However, they permit the receiver to have high sensitivity and dynamic range.

7. Carrier-to-noise ratio of optical photodetector output signals.

As shown in Figure 7, analog modulation of the laser diodes is used for broadband supertrunking applications.

In this scheme the time-varying electrical signal s(t) is used to modulate directly the laser diode about some bias point I_b .

The transmitted optical power P(t) is therefore of the form

$$P(t) = P_t [1+m.s(t)] \qquad (3)$$

Where P_t is the DC optical power, s(t) represents the combined analog FM signals and m is the modulation index defined as

$$m = \frac{\Delta I}{I_b - I_{th}} \qquad (4)$$

Where ΔI is the peak modulating signal and I_{th} is the threshold current

At the receiving end the photocurrent generated by the intensity modulated optical signal is given by

$$i_s(t) = Ip.G[1+m.s(t)] \qquad (5)$$

Where G is the photodetector gain and Ip again is the (unmultiplied) photocurrent generated.

If s(t) is a sum of N sinosoidally FM modulated signals, then the mean square signal current is

$$\langle i_s(t)\rangle = (1/2).\{G.m.Ip/N\}^2 \qquad (6)$$

It can be shown (Reference 1) that the mean square noise current for a photodiode receiver is the sum of the mean square quantum noise current, the equivalent resistance thermal noise current, the dark noise current and the surface leakage noise current. Therefore, the total mean square noise current $\langle i_N(t)\rangle$ is given by

$$\langle i_N(t)\rangle = 2.q(Ip+I_D).G^2.F(G).B+2.q.I_L.B+ (4.K_b.T.B).F_a/R_eq \qquad (7)$$

Where F(G) is the excess photodiode noise factor = G^x $(0<x<1)$, B is the equivalent noise bandwidth of the detector, R_{eq} is the equivalent resistance of the photodetector load and amplifier, F_t is the noise figure of the low noise preamplifier, I_D is the (unmultiplied) dark current, I_L is the surface leakage current, T is the equivalent noise temperature of the preamplifier and K_b is the Boltzman constant.

The carrier-to noise ratio of the FM-modulated analog signals at the output of an optical detector (and before FM demodulation) is given by

$$C/N = \langle i_s(t)\rangle \,/\, \langle i_N(t)\rangle \qquad (8)$$

The term $(4.K_bT.B).F_a/R_{eq}$ represents the circuit noise and the term $2q(Ip+I_D).G^2.F(G).B$ the quantum noise (and dark current) associated with a photodetector.

When an avalanche photodiode is employed at low signal levels, and with low values of G, the circuit noise term dominates. At a fixed low level, as the gain is increased from a low value, the C/N increases with the gain until the quantum noise becomes comparable to the circuit noise. As the gain is increased further, the C/N decreases as $F(G)^{-1}$.Thus, for a given set of operating conditions, there exists an optimum value of the avalanche gain for which the C/N is maximum.Since an avalanche photodiode improves the C/N for small optical signals, it is the preferred photodetector for this situations.

For very large optical signals the quantum noise dominates the receiver noise. In this case the avalanche photodiode can decrease the C/N of the received signals if the gain is not decreased or optical attenuation inserted.

8. FM system performance in fiber optic supertrunks.

If analog FM modulation is used to transmit video, we can define the weighted output SNR_{ow} (Ref.2) of a video-modulated carrier as a function of the input $(C/N)_{IF}$, the modulation index β, the IF bandwidth B_{if}, and the highest baseband video frequency F_m as follows

$$SNR_{ow} = [3.\beta^2 B_{if}/(2.Fm)] + (C/N)_{IF} + W \quad (9)$$

Where $(C/N)_{IF}$ is measured in the IF bandwidth and

$$B_{if} = 2 \times (\Delta F + Fm) \quad (10)$$

B_{if} is the Carson's rule bandwidth and the modulation index is

$$\beta = \Delta F/Fm \quad (11)$$

where ΔF is the peak deviation of the video carrier and W is the video weighting improvement resulting from using preemphasis and deemphasis (3.6db with CCIR-405-1 characteristic) , CCIR noise weighting (11.5db) and P-P/RMS conversion (9db).

Note that ΔF is the peak deviation of the carrier by a **sinusoidal** signal with no preemphasis included.Other deviation definitions, used by equipment manufacturers (including Catel) include **sync tip to peak white deviation** $\Delta F_{st\text{-}pw}$. It can be shown (Ref. 4) that the two deviation definitions are related as follows:

$$\Delta F = \Delta F_{st\text{-}pw} / (2x0.3) \quad (12)$$

If we refer the noise generated by the receiving equipment to the input, the carrier to noise ratio C/N becomes

$$(C/N)_{IF} = Pr/(kT^0{}_{eq} x B_{IF}) \quad (13)$$

Where k is the Boltzman constant, $T^0{}_{eq}$ is the equivalent noise temperature given by:

$$T^0{}_{eq} = T^0{}_0 x(F-1) \quad (14)$$

in which $T^0{}_0$ is the ambient noise temperature (300^0K) and F is the noise figure of the receiver.

To estimate the theoretical achievable performance of a multichannel FM video modulation system, the SNR_{ow} will be calculated with the following assumptions:

Carrier deviations :

$\Delta F_{st\text{-}pw}$ = 4Mhz , 6Mhz

(corresponding to ΔF = 6.67Mhz, 10Mhz)

IF Bandwidth B_{IF} = 30 Mhz, 40Mhz

Worst case NF : 20 db (to account for multichannel operation),

Worst received power : -26 dbm (From the optical link power budget),

Substituting in equations (9) to (14), the SNR_{ow} becomes:

For $F_{st\text{-}pw}$=4Mhz and IF bandwidth=30Mhz,
SNR_{ow} = 72 db.

For $F_{st\text{-}pw}$=6Mhz and IF bandwidth=40Mhz,
SNR_{ow} = 75 db.

Although not shown in the analysis, it has been demonstrated that FM can reject interference from other sources including adjacent FM channels, intermods, crossmods and any other interference not coherent with the in-channel video. This feature permits the system designer to select the modulation to cost-effectively design high performance multichannel video FM systems over broadband supertrunks

Early multichannel FM video systems using peak carrier deviation of 1.6 Mhz and RF bandwidth of 16 Mhz have been used in coaxial cable supertrunks and achieved S/N_0 improvement factors of 10 db over the C/N_i.

Table 1: Link budget for 16 channel CATV supertrunk

Transmitter	
A. Minimum optical power	-1.5 dbm
B. Connector loss	0.8 db
C. Launch power	-2.3 dbm
Receiver	
D. Receiver sensitivity	-26.0 dbm
E. Degradation allowance	1.0 db
F. Minimum Input power	-25.0 dbm
Fiber link loss	
G. Fiber loss (0.4 db/km)	16.0 db
H. Splice loss (0.3 db/km)	3.3 db
I. Total link loss	19.3 db
System	
J. System gain	22.7 db
K. System margin	3.4 db

9. Link budget for analog FM video fiber optic system

A typical link budget for a 16 channel CATV supertrunk is given in Table 1.

The laser transmitter average optical power is -1.5 dbm. Up to 0.8 db can be lost in the connector, resulting in total launched power of -2.3 dbm.

The receiver sensitivity is defined as the average input power at the receiver which yields a weighted video signal to noise ratio of 60 db with full 12 channel loading. From the previous section and allowing for multichannel derating, this input power is -26 dbm. An allowance of 1 db is allocated to degradations due to temperature and aging, resulting in required input power of -25 dbm.

A fiber link of 25 miles (40 km), using 0.4 db/km and cable sections each 4 kilometers (slicing loss of 0.3 db/splice, 11 splices) will result in 19.3 db of optical attenuation and will yield a system margin of 3.4 db.

An example of present state-of -the art high performance wide deviation video FM systems delivered by Catel is shown in Figure 9. The system is carrying 12 channels, each 40 Mhz wide with multiple subcarriers at a distance to 40 km and achieving more than 65 db video S/N_0 per channel.

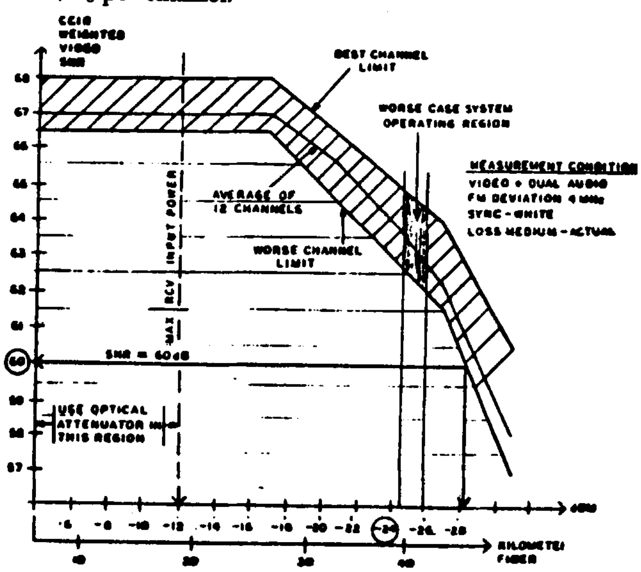

Figure 9: S/N_0 of a 12 channel FM system over a single mode fiber media

The chart shows that worst case of 60 db S/N_0 per channel at 40 km distance can be achieved with worst case received power of -28 dbm and dual audio channels.

10. Flexibility of fiber optic video FM systems

In addition to its high performance, video FM system can also be quite flexible.

For example, the system can be easily adapted to transmit data. Since multi-level PCM data is a video-like signal, PCM multiplexers can be readily interfaced (as shown in Figure 9) with the FM modulator and demodulator permitting high data rate signals to be transmitted over broadband networks.

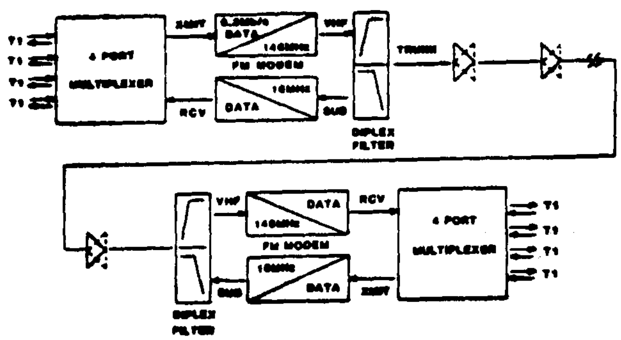

Figure 9: PCM multiplexer interfaced to an FM system

Other type of complex signals (such as BTSC - stereo audio signals) can be conveniently and efficiently carried as subcarriers above the audio subcarrier signals.

11. Future directions of fiber optic systems

What direction of the future for fiber optic systems will take depends mainly on the applications being developed today.

For long haul analog or digital data transmission, 1550 nm seems a natural extension of the present 1300 nm systems.

For the local loop application, it seems that low cost repeaters and fiber optic to coax cable converters would be very desirable. Future developement of the laser transmitters/receivers allowing direct FM modulation of the light beam would help lower the cost and increase the performance. Finally, development of coherent demodulation methods for lightwave signals will extend the range of the transmissions by several orders of magnitude. Lets hope and work on it to bring it closer to reallity!

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Dr. Mircho A.Davidov has received his PH.D. in 1981 from the University of Southern California and Msc and Bsc in 1976 and 1974 respectively from Tel Aviv University.

Dr. Davidov presently directs all of the engineering activities at Catel Telecommunications Inc. developing products in the areas of FM modulators and demodulators for video transmission, VSB-AM modulators and demodulators, FDM-FM fiberoptics transmitters and receivers and frequency translators for LAN data signals.

He was Director of Corporate Research at Oak Industries from 1981-1985. His responsibilities at Oak included developing systems for securing the transmission of high quality video signals. He worked for Honeywell and Brunswick Corporations between 1979-1981 and was responsible for development of RF communication systems for wireless monitoring of energy and control systems and wireless transmission of language translations. Between 1976-1979 he was a consultant to LinCom Corporation in Los Angeles, performing studies in the area of PLL, synchronization and signal processing for satellite communications.Between 1970-1976 he was an engineer for the Israeli Governmental Communication Office,designing circuits for the International Telephone,Telegraph and Telex lines. Between 1967 and 1970 he managed a military communication lab designing communication equipment for the Israeli Defence Forces.

He was an assistant professor at Cal State Northridge in 1981 and teaching assistant between 1974-1979 at Tel Aviv University and the University of Southern California. He speaks 5 languages fluently and is a member of IEEE.

Dr. Davidov has numerous publications and 7 patents pending.