PROPERTIES AND SYSTEMS CALCULATIONS OF OPTICAL SUPERTRUNKS FOR MULTICHANNEL TV TRANSMISSION, USING ANALOG INTENSITY MODULATION, SINGLE MODE FIBERS AND HIGH DEVIATION FM

Hermann Gysel

SYNCHRONOUS COMMUNICATIONS INC.
SAN JOSE, CA 95131

ABSTRACT

Optical supertrunks are being installed in an increasing number. The technology is mature and the prices are getting attractive. It is shown here how transmission bandwidth, transmission quality and optical loss budget can be used as planning elements for the determination of system parameters as modulation, frequency plans, and drive levels in an analog fiber optic transmission link.

I. INTRODUCTION

TV multichannel transmission has been tried in the past decade mostly with mediocre success, especially when multimode fiber was used. Now we have learned to use the right fiber, the right modulation, and the right frequency plan to avoid noise and intermodualtion problems so that we can transmit channel numbers and video signal qualities that a few years ago were unthinkable.

II. THE TRANSMISSION BANDWIDTH OF SYSTEMS USING SINGLE MODE FIBERS

A: The transmission bandwidth of the laser/fiber combination

The transmission bandwidth of the laser/fiber combination can be derived from the systems response to a Gaussian pulse, using the Fourier transform [1]. A good approximation for the total rise time is [2]:

$$t_{rise,tot} = \left(t_{laser}^2 + t_{fiber}^2\right)^{1/2} \quad (1)$$

In a single mode fiber intermodal dispersion is nonexistent. Among the intramodal dispersions chromatic (or material) dispersion is predominant [3]. Chromatic dispersion is a function of the dispersion property of the fiber used, the fiber length and the spectral width of the laser. The rise time of a pulse propagating thru a fiber is therefore

$$t_{fiber} = D_c \times \Delta\lambda \times L \quad (2)$$

with D_c : Chromatic dispersion of the fiber (ps/nm–km)
$\Delta\lambda$: Spectral width of the laser diode (nm)
L : Length of the fiber (km)

The electrical 3 dB bandwidth can now be calculated to be [1]:

$$B_{3\,dB} = 0.375/t_{rise,tot}$$
$$= 0.375/\left[(D_c \times \Delta\lambda \times L)^2 + t_{rise,laser}^2\right]^{1/2} \quad (3)$$

The presently most often used wavelength is 1300 nm where the fiber loss is low, typically 0.5 dB or even less and dispersion is zero using low loss oxide-glass fibers. For the even lower loss wavelength 1500 nm two kinds of fibers are available or in development: Dispersion shifted or dispersion flattened [4]. Most fibers that are installed today are dispersion nulled at 1300 nm. Using a laser at that wavelength the bandwidth in (3) becomes independent of the fiber length. Typical rise times of InGaAsP lasers are around 0.3 ns so that the transmission bandwidth of this laser/fiber combination is above 1 GHz. Figure 1 shows the chromatic dispersion coefficient of a typical single mode fiber:

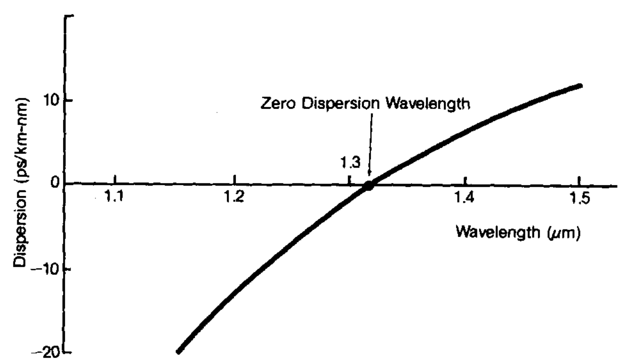

Figure 1: Chromatic dispersion coefficient of a typical single mode fiber

Using (in a WDM application with 1300 nm) a typical 1550 nm InGaAsP laser diode with a spectral width of 4 nm and a chromatic dispersion of 13 ps/km-nm, the resulting bandwidth of a 30 km link can be calculated using (3) to be only 240 MHz. Recently DFB laser diodes with a spectral width of only 0.1 nm have become available. Chromatic dispersion can then be neglected for the above mentioned fiber for lengths up to about 70 km.

B: The receiver bandwidth

The receiver rise time can be included in equation (3). Typical receiver bandwidths are 600..700 MHz using Ge APD's that are easily available and 1 GHz or higher using faster InGaAs APD's or PIN detectors.

III. CHANNEL SPACING

A: Channel spacing, deviation, and video bandwidth

The bandwidth of a frequency modulated signal is approximately

$$B = 2 (D_p + f_m) \qquad (4)$$

with D_p: Peak deviation

f_m : Modulation frequency (4.2 MHz for NTSC)

Deviation is often expressed as the deviation of the non-emphasized part of the video signal. It is called "Sync tip to peak white" (STPW) Deviation. If the video signal is pre-emphasized in accordance to CCIR Rec. 405 (525 lines) equation (4) becomes

$$B = 2 (D_{STPW} / 1.64 + f_m) \qquad (5)$$

As pointed out earlier, transmission bandwidths over 1 GHz with fiber lengths, that are limited mostly by the minimum optical receive power, are feasible today. The number of channels per fiber is a trade off versus video quality. Reasonable video specs (EIA-250-B long haul) can be achieved with channel numbers up to approximately 24 channels per fiber. Having a 30% guard band between adjacent channels, deviations below 8 MHz STPW are not optimum. A deviation of 800 kHz STPW as used in older coaxial FM equipment is useless on fiber.

B: Channel spacing as required by the adjacent channel protection ratio

The adjacent channel protection ratio is expressed here as the video signal to periodic noise ratio SPR_{video} :

$$SPR_{video} = 20 \log (100 \text{ IRE} / V_{interference,pp}) \qquad (6)$$

This definition of periodic noise is used in the EIA standard EIA-250-B [5] as well as the CCIR[6]. Figure 2 shows the measured SPR_{video} (using a Rode & Schwarz UPSF2 noise meter) as a function of the frequency separation of a wanted channel and its adjacent. Both carriers are frequency modulated with 8 MHz STPW. No transmit filter is used in this test. The receiver filter has a bandwidth of 29 MHz. The video modulation of the wanted channel is "flat field", the one of the interfering adjacent is "pulse and bar" with a 30 IRE subcarrier at 6.2 MHz. A live video signal gives slightly better results.

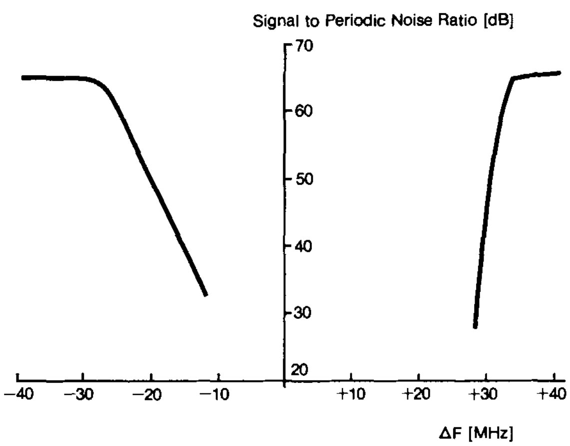

Figure 2: Adjacent channel protection ratio for 8 MHz STPW deviation

Figure 2 shows that without transmit filtering a channel spacing greater than 36 MHz is feasible, with or without using a subcarrier, when the STPW deviation is 8 MHz and the receiver filter bandwidth is 28 MHz. For other deviations or filter bandwidths this test has to be repeated.

IV. INTERMODULATION DISTORTIONS

A: Second order distortion and frequency planning

In a laser diode second order distortions are predominant. A way to get around these intermodulation products is using only an octave of the available frequency spectrum [7]. This is useful, when vestigial sideband signals are transmitted. The situation is totally different, when wideband FM is used instead. Figure 3 shows the protection ratio when an unwanted signal with 16 MHz deviation is tuned thru a wanted one with a deviation of 8 MHz. As in the adjacent channel protection ratio the video modulation of the wanted signal is "flat field", the one of the unwanted signal is "pulse and bar" with a 30 IRE subcarrier at 6.2 MHz.

Here the protection ratio is the ratio of wanted to interfering signal power in dB which is necessary to achieve a video signal to periodic noise ratio of 60 dB. It is possible to extrapolate between protection ratios at center frequency for different deviations than 8 MHz STPW using 20 log (D1/D2) as a correction factor.

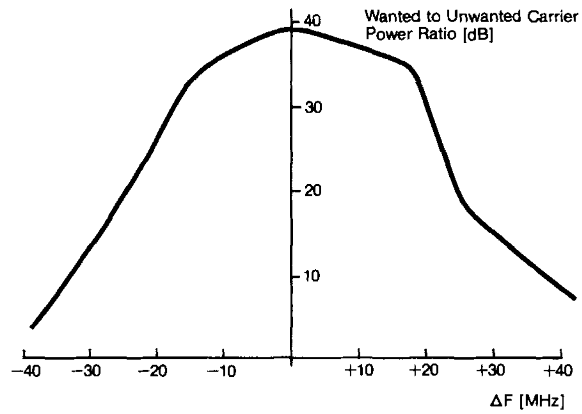

Figure 3: Protection ratio for a 16 MHz deviation signal interfering one with 8 MHz deviation for 60 dB signal to periodic noise ratio

A second order efficient frequency plan, suggested by Synchronous and used and described by [9], has the channel frequencies

$$f_{ch} = f_s/2 + n \times f_s \qquad (7)$$

with f_{ch}: channel frequency [MHz]

f_s : channel spacing [MHz]

n : channel number (integer).

All second order products f_{IM2} have the form

$$f_{IM2} = m \times f_s \qquad \text{(m: integer)} \qquad (8)$$

which means that they fall between channel frequencies.

From figure 2 can be concluded that with a channel spacing of 36 MHz or more second order products can be as high as −12 dBc. The efficiency of this frequency plan is therefore 27 dB, when compared to the situation where the products fall on the center frequency. Using (7) allows to ignore second order products because now third order products become predominant.

B. Third order distortion

The weakly nonlinear region and the clipping region

Intermodulation analysis is performed for the weakly nonlinear region of a nonlinear device using a power series approach [9] to determine the relative power of intermodulation products. A useful parameter of a nonlinear device is its third order intercept point [10). If it is a constant then the power series approach is justified. We have measured the third order intercept points of several InGaAsP single mode lasers with a wavelength of 1300 nm. Their average third order two tone input intercept point power was 22 dBm at 100 MHz, the standard deviation of 5 samples was 4.3 dBm. It decreases with frequency between 100 and 800 MHz by 7 dBm.

When a laser diode is instantaneously driven near its threshold then the laws of the weakly nonlinear region are not valid anymore. Typical laser diodes reach this clipping region with a two tone power of 0.5 mW per tone. Typical measured total input powers into the InGaAsP lasers we use with a 12 channel signal for optimum performance varies from 2 to 5 dBm. This indicates that the laser diode is not used in its weakly nonlinear region and that classical composite triple beat ratio calculations can not be used anymore.

The laser intensity modulation as a function of the number of channels

We found empirically, that using a depth of intensity modulation m of 0.8 the drive level has to be decreased by

$$\Delta L_{RF} = K(N) \times \log(N) \quad \text{(dB)} \tag{9}$$

with ΔL_{RF} : Decrease in RF drive level

K(N) : 18 for $N< 8$,

16 for $12<N<18$,

15 for $N<28$

N : Number of channels.

The RF drive level is therefore so adjusted that the RF signal peaks reach into the clipping region of the laser. Here the composite triple beats increase by more than 3 dB per dB signal increase until carrier to beat power ratio is around 40 dB, where it affects the video SNR rapidly.

V. CARRIER TO NOISE AND VIDEO SIGNAL TO NOISE

A: Carrier to noise ratio as a function of received optical power and depth of intensity modulation per carrier

Using an APD receiver followed by a transimpedance amplifier the carrier to noise ratio CNR can be approximated by

$$CNR = \frac{(m_i \times R \times P_r \times M)^2/2}{(RIN \times R^2 \times P_r^2 \times M \times B) + 2q\,(R \times P_r + I_d) B M^{2+x} + (4KTB/R_f)F} \tag{10}$$

with
CNR : Carrier to noise ratio (4.2 MHz noise bandwidth)
m_i : Modulation index of the i-th carrier
P_r : Received optical power (W)
R : Responsitivity of the APD (A/W)
M : Multiplication factor of the APD
x : Excess noise factor of the APD
I_d : Dark current of the APD (A)
RIN : Relative intensity noise of the laser diode (W/Hz)
B : Noise bandwidth (4.2 MHz)
q : 1.6E-19
k : 1.4E-23
T : Temperature (K)
R_f : approx. the transimpedance
F : Noise figure of the transimpedance amp.

The three terms in the denominator of equation (10) indicate, that an optical transmission system can be laser limited (the RIN term predominates), quantum noise limited (the seocnd term predominates) or receiver limited [11].

In short optical links (total loss less than 15 dBm) the use of a PIN detector (M=1 in (10)) is adequate. The biggest problem in short links is the laser sensitivity to reflections that are produced by connectors, splices and the detector itself [12]. This problem is harder with single mode than with multimode fibers. The reflection coefficient at the laser itself is a function of the reflection coefficient of the connector etc. and of the coupling efficiency between laser and fiber [13]. For that reason laser diodes are available with a low coupling efficiency and therefore a lower output power (−6..−10 dBm). We observed with optical losses below 10 dB and efficiently coupled lasers RIN degradations of over 10 dB. This would make a low loss link with a potential to transmit 8 channels with more than 67 dB video SNR unpredictable. Recently substantial improvements in connector design have been reported [14].

In medium length optical links, where quantum noise predominates, the choice of the right APD is critical. Using a InGaAs APD instead of a Ge APD can increase CNR by as much as 6 dB in this region.

At high optical losses the receiver noise is the limiting factor. For a given optical receive power P_r an optimum APD gain can be calculated:

$$M_{opt} = \left[\frac{4kTF / R_f}{q\,(R \times P_r + I_d)\,x}\right]^{1/(2+x)} \tag{11}$$

Because R_f is indirectly proportional to the receiver bandwidth, a careful tradeoff has to be made between the optical loss budget and the transmission bandwidth when optical losses are high.

B: Video SNR as a function of the CNR of the optical receiver

As described above a good prediction of CNR is possible by using m=0.8 in (10) and by reducing the resulting CNR in accordance with (9). The video SNR is a linear function of CNR above the FM detector threshold. Various CNR/ video SNR relations exist, depending on EIA or CCIR weighting, 100 or 140 IRE reference etc. [15]. We have verified using the Rode & Schwarz noise meter for video SNR, and the Tektronix spectrum analyzer 7L13 as well as the power meter HP 435 B for CNR the equation

$$SNR_{video} = CNR_{4.2} + 12 + 20 \log (D_{STPW}) \quad (12)$$

with SNR_{video} : CCIR weighted Video SNR, referenced to 100 IRE

$CNR_{4.2}$: CNR with 4.2 MHz noise bandwidth

D_{STPW} : Sync tip to peak white deviation ($=D_{pp}$ / 3.27)

C. Performance of 8, 12, and 24 channel transmission systems

Systems with 8 and 12 channels on one fiber have been installed in the past [8]. With 12 channels we measured typically video SNR's better than 63 dB for optical losses that are less than 24 dB. To find the limit of our present optical fiber transmission system we run a test transmitting 24 channels with 4 MHz deviation (STPW) and an optical loss of 16 dB. Equation (10) and (12) predicted a video SNR of approximately 57 dB. Reading the CNR in figure 4 (Spectrum analyzer correction factor 2.5 dB) to be around 34 dB verifies the predicted video SNR. This experiment shows that very high channel densities on one fiber can be realized using high deviation FM if the signal quality does not have to be very high.

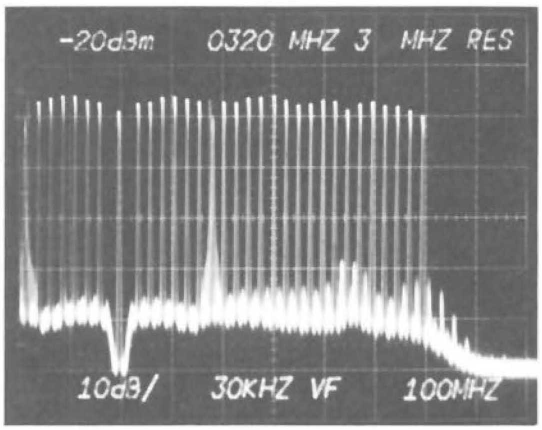

Figure 4: 24 channels over 16 dB of optical loss

VI. THE TRANSMISSION OF BTSC STEREO OVER FIBER

The transmission of stereo audio signals over fiber can be done using subcarriers or carriers at discrete frequencies. Discrete audio carriers are normally preferred because there is no interaction between audio and video. The EIA-250-B standard prescribes methods of measurement for audio SNR (video flat field with 50 IRE) and periodic noise with audio on and video off that do not allow to catch these interactions. Systems with 70 dB specified audio SNR have shown over 20 dB lower SNR with certain video waveforms. Synchronous has designed a high deviation audio transmission family. 4.5 MHz intercarriers are multiplied and transmitted with a 4 times higher deviation than the original. Stereo separation as well as audio SNR has been proven to be unaffected by this transmission scheme in field tests that Synchronous run with Gill Cable in San Jose.

VII. THE TRANSMISSION OF SCRAMBLED SIGNALS OVER FIBER

Frequency modulators are usually phaselocked so that the average output frequency is at the nominal center frequency. They are therefore acting as highpass filters with a cutoff frequency equal to the natural frequency of the PLL. DC can only be restored at the receiver with a sync driven clamp. Scrambling systems that use baseband scrambling have therefore to provide a clamp pulse that can be transmitted on a subcarrier to restore DC of the scrambled video signal at the receiver. More difficult is the transmission of RF-scrambled signals. The method of transmitting a VSB signal at a video frequency [16] has shown to be hard to realize. Linearity problems of the FM modem prohibit using a VSB carrier around 1.5 MHz. An inverted spectrum needs substantially higher deviations to get marginal video SNR's.

VIII. CONCLUSIONS

The transmission of multichannel TV up to 24 channels per fiber over optical links has reached a high degree of maturity. The user can take a choice between video signal transmission quality, number of transmitted channels and optical loss budget by selecting the right components at the transmit and receive end. Using the given equations, frequency plans and protection ratios, the planning of an optical trunk is straightforward.

Transmit filtering is not necessary when high deviation FM is used.

Using subcarriers affects the channel spacing very little, but discrete audio carriers avoid any interaction between audio and video.

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