An 80-Channel High-Performance Video Transport System Over Fiber Using FM-SCM Techniques for Super-Trunk Applications

R.F. Kearns, V.S. Shukla, P.N. Baum, and L.W. Ulbricht

GTE Laboratories Incorporated
40 Sylvan Road
Waltham, MA 02254

ABSTRACT

Use of microwave subcarrier multiplexing (SCM) for transmission and distribution of a large number of video channels over optical fiber offers an attractive alternative to existing coaxial and multi-fiber systems. This paper describes a SCM system carrying 80 FM video channels, achieving a 60 dB SNR and an optical power budget of 14 dB. A transmission distance of 20 km with a 3 dB margin was also achieved without degradation. Such a system can be used in next-generation CATV super-trunk-type applications. Superior performance in terms of SNR and optical power was achieved by implementing the system based on optimization and judicious choice of parameters affecting its performance. The frequency plan, based on 9 MHz frequency deviation, uses the 3–6 GHz frequency band. The system uses high-frequency lasers having a 10 GHz bandwidth and RIN below –140 dB/Hz.

1. INTRODUCTION

Fiber-based super-trunk systems are currently used to provide high-quality FM video transmission between headends and several CATV hub locations.[1] Present-day commercially available systems,[2] using FM techniques, carry up to 16 video channels per fiber and offer hightransmission performance (SNR $\geq$ 60 dB). Transport of 80 high-quality video channels would require operating five of these 16-channel systems in parallel, necessitating use of multiple fibers and the associated optical transmitters and receivers.

FM-SCM (microwave subcarrier multiplexing of frequency-modulated video) has recently been shown to be an attractive alternative for transmission and distribution of a large number of video channels over a single fiber.[3–7] FM-SCM uses high-frequency lasers and photodetectors to access the frequency region above 1 GHz. Olshansky et al.[4–6] have reported SCM systems in the 2.7–7.6 GHz region carrying 60 and 120 FM video channels. For weighted SNR of 56 dB, the optical power budget was 14 dB. Way et al.[7] transported 90 FM video channels in the 1.7–6.2 GHz band over fiber and also achieved a weighted SNR of 56 dB with an optical power budget of 12 dB. The 56 dB SNR of most of the reported FM-SCM systems is less than the 60 dB preferred for super-trunk applications.

This paper describes a FM-SCM system for the next-generation high-capacity super trunk carrying 80 video channels over a single fiber with a 60 dB SNR that achieves an optical power budget of 14 dB. The first section develops an analysis of the fiber-optic system. This is followed by a discussion of the frequency plan and system implementation. The final two sections discuss the experimental results of laboratory measurements on a prototype system and the conclusions.

2. ANALYSIS

For super-trunk transmission systems, a high source SNR is required to ensure that a high-quality signal reaches the end-user. The SNR of any channel in a multichannel system can be described as shown in equation 1.

$$SNR_w = \{CNR_{if} + 10\ \mathrm{Log}(B_{if}/B_{bb})\} + A + 20\ \mathrm{Log}(1.6F_d/B_{bb}) \quad (1)$$

Where:

- SNR_w = Weighted video signal-to-noise ratio
- CNR_{if} = Carrier-to-noise ratio in the IF bandwidth
- A = 20.37 dB — made up of weighting, de-emphasis, and conversion factors
- B_{bb} = Baseband filter bandwidth
- B_{if} = Intermediate frequency bandwidth (IF)
- F_d = FM deviation — sync tip to peak white (STPW)

This equation is frequently referred to as the FM advantage equation since the last two terms represent the improvement in the detected signal as a result of employing FM modulation. From this equation, the FM deviation required to yield the same SNR performance for an 80-channel system as that of the 16-channel system can be calculated. If it is assumed that the same amount of total modulation power is available in both cases, an FM deviation of 2.2 times that of a 16-channel system is required for operation of an 80-channel system for the same figures. Commercial fiber-optic systems use about 4 MHz FM deviation for a 16-channel system, implying that a super trunk employing 80 channels would require a 9 MHz deviation.

Another important factor in the specification of a super trunk is the optical power budget. It is simply the difference between the optical power required at the receiver and the laser-coupled power. To calculate the received power, the carrier-to-noise (CNR) equation must be solved, which includes the major noise terms that cause impairment in the signal. The CNR is expressed as shown in equation 2.[8] The terms of the equation have been arranged to show the dependence of CNR on optical power and modulation depth.

$$CNR_{if} \geq \frac{0.5}{\dfrac{kTBN_F}{R_f(mR_dP_s)^2} + \dfrac{2eB}{m^2R_dP_s} + \dfrac{B(RIN)}{m^2} + C_2m^2N_2 + C_3m^4N_3}. \quad (2)$$

Where:

- m = Modulation depth per channel
- R_d = Photodetector responsivity
- R_f = Amplifier input impedance
- k = Boltzmann constant
- T = Absolute temperature
- B = IF bandwidth
- N_F = Noise figure of amplifier
- P_s = Received optical power
- e = Electronic charge
- RIN = Relative intensity noise
- C_2 = Second-order intermod coefficient
- C_3 = Third-order intermod coefficient
- N_2 = Number of second-order products
- N_3 = Number of third-order products

The first term in the equation represents the impairment due to thermal noise, while the second and third terms are the shot and relative intensity noise (RIN) impairments, respectively. The last two terms are the degradation due to the second-order and third-order intermodulation distortion.

Examination of equation 2 reveals some general trends in achieving a given CNR. Increasing optical power increases CNR for the terms involving thermal and shot noise. Increasing optical power does not change the CNR for terms involving RIN and intermodulation noise. Consequently, these latter impairments cannot be lowered by increasing the optical power. Increasing the modulation depth increases the CNR for terms involving thermal, shot, and RIN noise while decreasing the CNR for terms involving intermodulation noise. Thus, there is an optimum value of modulation depth where the thermal, shot, and RIN terms are balanced off against the intermodulation terms.

In wideband microwave systems, 50 Ω amplifiers are employed. Under these conditions, the shot noise will be small. In a thermally noise limited system with no intermodulation distortion, the optical power is proportional to the square root of the CNR. Equation 1 shows that a doubling of the frequency deviation yields a 6 dB SNR improvement. However, since the optical power is proportional to the square root of the CNR, only a 3 dB gain in received optical power is realized. This reveals that while increasing the frequency deviation results in a one-for-one increase in the SNR, only half the increase in the optical power budget is realized.

Figure 1 shows the effect of RIN as a function of modulation depth for a 9 MHz FM system. For this figure, a 50 Ω amplifier with a noise figure of 2.5 dB was assumed for the thermal noise model, and a PIN photodiode was used to predict the shot noise. In order to achieve the highest optical power budget, it is desirable to operate at as high a modulation depth as possible. If the modulation power is divided equally between all the channels, the modulation index is 100%/80, or 1.25%. This would produce only a modest level for the optical power budget while placing a severe constraint on the laser's RIN. Typical values for laser RINs are between −130 dB/Hz and −145 dB/Hz, depending on, among other things, the operating frequency. It has been reported that higher levels of modulation per channel are possible since not all the channels will carry the maximum power at one time.[6] Levels of modulation of 6% to 8% would negate the impairment and thereby maximize the optical budget. However, the higher modulation levels will be limited by the intermodulation distortion, as discussed in the next paragraph.

To determine the nonlinear impairments in the FM-SCM system requires the knowledge of the coefficients C_2 and C_3 used in equation 2. These coefficients have been calculated by the following equations.[9,10]

$$C_2 \approx 0.5\,(f/f_r)^2\,R(f) \tag{3}$$

$$C_3 \approx [\{(f/f_r)^4 - 0.5(f/f_r)^2\}^2 + (2\pi\tau_p f_r)(f/f_r)^4]^{1/2}\,R(f)R(2f) \tag{4}$$

$$R(f) = \{((f/f_r)^2-1)^2 + (f\Gamma)^2/(2\pi f^2)^2\}^{-1/2} \tag{5}$$

Where:

$R(f)$ = Small-signal frequency response
f_r = Relaxation resonance frequency
Γ = Damping rate $\approx 0.32 \times 10^{-9}\,(f_r)^2$
τ_p = Photon lifetime

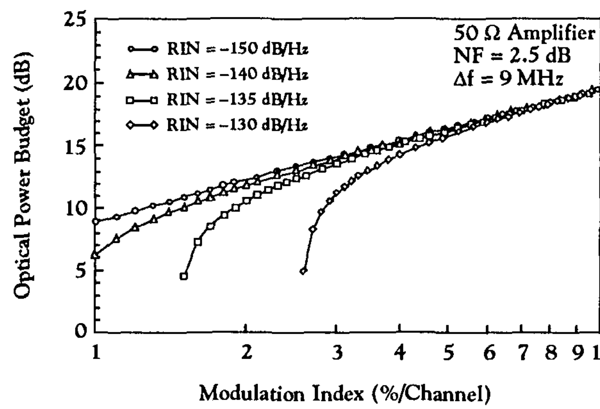

Figure 1. Optical Power Budget As a Function of OMI for Different RIN Values.

The values calculated by these equations were derived using a small-signal model for the laser. The results are expected to be optimistic since the modulation levels investigated here constitute large-signal behavior. Figure 2 shows a plot of second-order and third-order distortion coefficient as a function of carrier frequency for a laser with a 9 GHz resonance frequency. The third-order term peaks at the resonance frequency and one-half the resonance frequency. The second-order terms increase to a maximum at the resonance frequency. Notice, however, that the impairment due to intermodulation distortion is also a function of the number of intermodulation products at a particular frequency. Thus some flexibility is possible to minimize the distortion by choosing a plan that minimizes the product of the intermodulation distortion coefficients and the number of intermodulation terms.

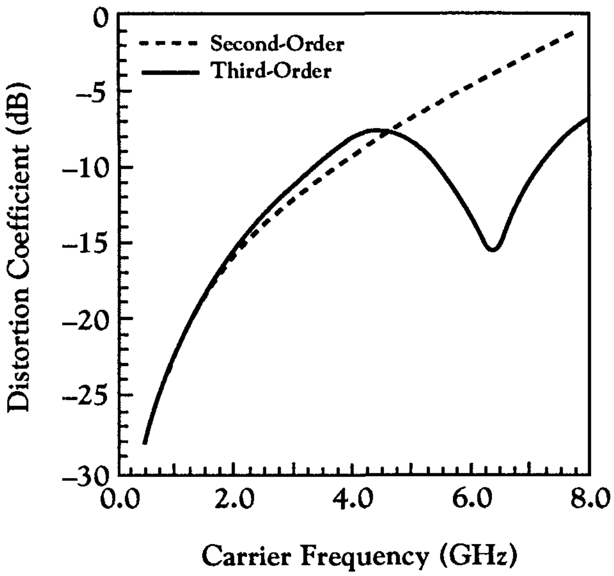

Figure 2. Laser Distortion,
Resonance Frequency = 9 GHz.

3. FREQUENCY PLAN

The selection of the frequency plan depends on many factors, including intermodulation distortion and laser frequency response. The use of an octave band of frequencies avoids the second-order distortion. The channel spacing must be selected taking into account the total bandwidth of the signal. The per channel bandwidth is dependent on the FM deviation. A 9 MHz deviation was specified as the minimum deviation required in order to achieve the required SNR (as discussed earlier). Larger deviations would use too much bandwidth. For this deviation, a channel spacing of 40 MHz was specified. Tests have verified that this spacing is adequate to pass the video signal with >60 dB SNR.[11] Assuming this channel spacing, a frequency span from 3.4 GHz to 6.7 GHz containing all 80 channels within an octave band was chosen.

4. SYSTEM IMPLEMENTATION

Figure 3 shows a simplified diagram of a FM-SCM video transport system. A number of FM-modulated video channels are up-converted to the microwave band and power-combined in the transmitter. The scheme uses block conversion of a number of channels to limit the component count needed to heterodyne the signals. The practical block size is limited by the filters that must reject unwanted images, local oscillator, and signal leakage. The composite microwave signal is used to intensity-modulate a wide-bandwidth laser. After transmission through a span of single-mode fiber and detection with a wide-bandwidth optical receiver, the microwave signal is down-converted and demodulated.

The system was implemented to verify the feasibility of using a fiber-optic link to transport 80 channels of video information. The unit consisted of a bank of 12 voltage-controlled oscillators modulated by 11 video sources and one test channel. The video sources were obtained from 11 satellite receivers receiving the standard satellite signals. The tests were done with no audio subcarrier. The test channel was modulated with a Tektronix 1910 video pattern generator. This bank of 12 channels was then block-converted into 7 contiguous frequency slots to produce an 84-channel system. No block conversion filters were employed for this stage of the tests. A notch filter was employed in the test channel to eliminate any impairment due to the microwave electronics. The sources were Ortel (10 GHz) lasers. An RF attenuator at the input of the laser was used to adjust the modulation level. An optical isolator was used after the pigtail of the laser to minimize reflections. A low-reflectance optical attenuator was used to evaluate the optical power budget. Selected tests were also conducted using optical fiber. The signals were detected with a wideband optical detector and a low-noise 50 Ω amplifier and down-converted to a satellite channel for demodulation by a satellite receiver. Signal analysis was performed using a Tektronix VM-700 video test set.

5. RESULTS

Figure 4 shows the test results of three lasers. For each level of modulation, the optical attenuator

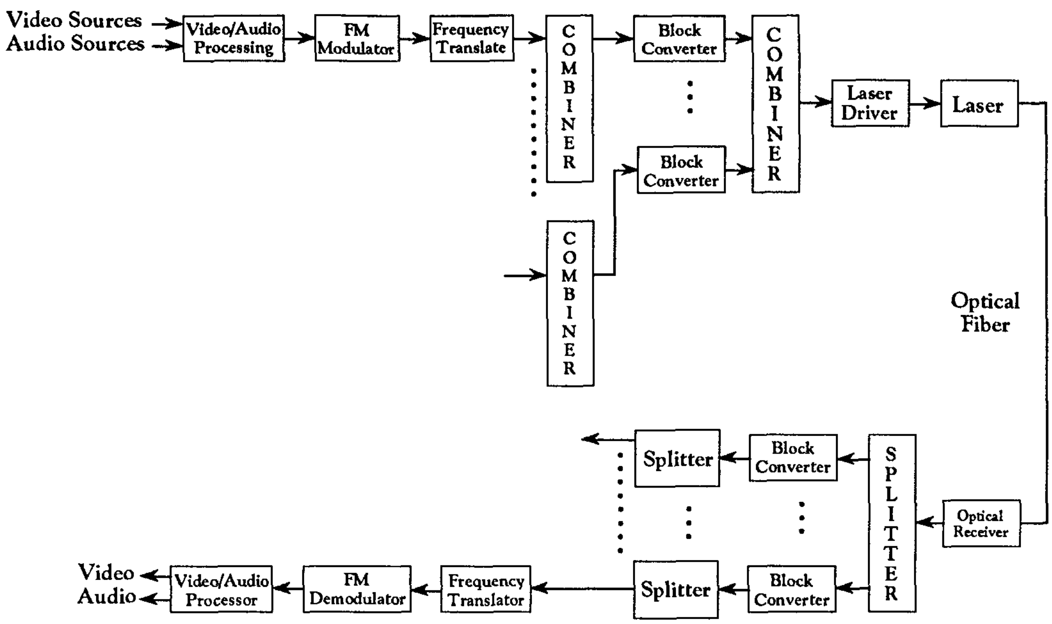

Figure 3. FM-SCM Transmission System Block Diagram.

was adjusted for a 60 dB SNR. The value of the optical attenuator plus the losses in the optical isolator and associated connectors were added to obtain the optical link budget. The curves were not normalized for laser power output, which accounts for the differing maximum values. The sharp fall-off at about 4%/channel modulation is attributed to the third-order intermodulation distortion. The dip in the center of laser 1 is considered measurement anomaly and was not a typical response. The computed simulation is shown as a dotted line. There is good agreement at low modulation levels, where thermal and RIN noise dominate. The agreement at high modulation levels is not good and suggests that further investigation into modeling laser large-signal behavior is warranted.

The system was also operated over 20 km of single-mode fiber. The fiber zero dispersion point was matched to within 10 nm of the laser central wavelength. Under these conditions, no dispersive effects were noted. The fiber attenuation was 0.5 dB/km. A 3 dB margin was recorded, resulting in an optical power budget of 13 dB exclusive of splices.

Another test was conducted to determine the sensitivity of SNR to optimum modulation index. Figure 5 shows the optical power budget as a function of modulation depth for three SNR ratios. As expected, the optimum modulation index is higher at lower SNR and the optimum range is broader. The optical power budget is also higher since the CNR requirement is lower, allowing more noise to be present in the system.

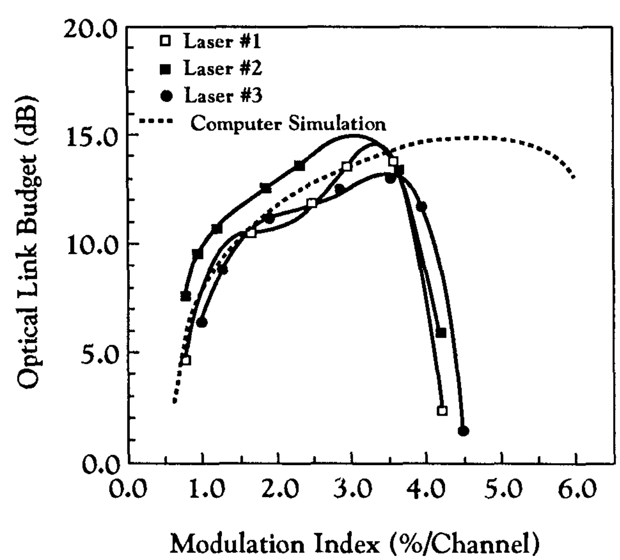

Figure 4. FM-SCM Performance, SNR = 60 dB.

6. CONCLUSIONS

This paper considers the use of FM-SCM techniques for the transmission and distribution of 80 video channels over fiber in a super-trunk-type environment. It identifies the effects ofvarious parameters on system performance. The optimization and judicious choice of FM-SCM parameters offers an opportunity to enhance the system performance and facilitate its practical implementation. An 84-channel FM-SCM system was implemented based on parameter optimization and current state-of-the-art components. By operating over an octave transmission band, the system had an optical power budget of about 14 dB at a 60 dB SNR, for an optimum modulation depth of 3.5%/channel.

The performance of FM-SCM systems should further improve with the recent availability of lasers having higher coupled power and improved high-frequency characteristics and linearity (viz. Ortel type 1530B). Use of high-frequency low-noise APDs should increase the receiver sensitivity and hence the power budget. It is estimated these two improvements would add 6 dB to the achievable power budget.

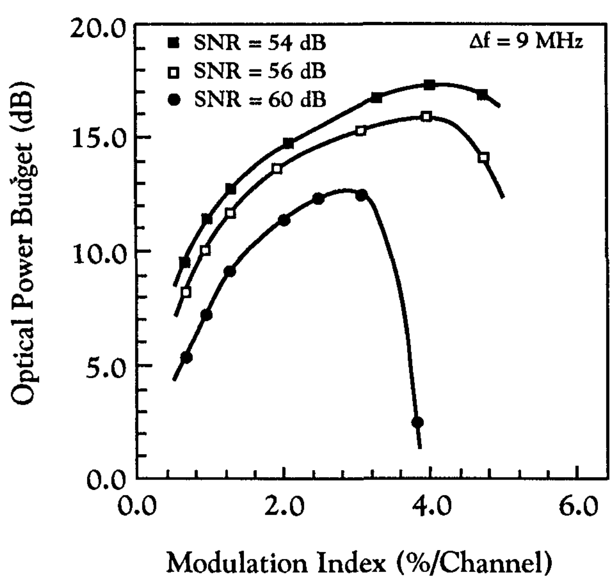

Figure 5. FM-SCM Performance.

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