Pulse Width Modulation for Analog Fiber-Optic Communications

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Abstract—**The pulse width modulation (PWM) technique has been revisited and analyzed to evaluate its merits for application to analog signal transmission in fiber-optic links. Fourier analysis of the PWM signal reveals that it can be used as a vehicle to launch an analog signal onto optical fiber when a symmetrical natural sampling process is used. The SNR of the modulated signal depends on the timing jitter of the carrier pulses and a wide-band (45 MHz) SNR of 45 dB has been obtained with a commercially available multimode laser transmitter. A linear dynamic range of over 50 dB has been experimentally demonstrated. The full fiber bandwidth can be utilized by using a very high pulse carrier frequency, while a more popular pulse frequency modulation technique provides about a 10-MHz analog signal bandwidth when 1 km of multimode fiber is used in conjunction with a short wavelength (0.87 μm) LED transmitter. Analog transmission capability was experimentally demonstrated by constructing a simple video link using common laboratory equipment. The performance of the video link supports the PWM modulation theory developed here and elsewhere. The experimental results indicated that PWM is potentially very attractive for low-cost broad-band local area network (LAN) application, including future highly interactive offices, hospitals, and automated factory floors.**

I. Introduction

ALL DIGITAL pulse code modulation (PCM) methods have been the preferred choice of fiber-optic transmission technology because of the inherent nonlinearity of optical sources (notably for laser diode), which makes it difficult to use direct analog modulation techniques for fiber-optic communication systems. Moreover, digital systems offer considerable advantages over an analog transmission technique. For example, PCM allows the reproduction of the original signal at the repeater station without sacrificing its quality and the temporary storage of the data at any repeater station along the transmission route.

However, despite the current dominant trend toward all-digital transmission in the optical communications industries, there may exist many potential applications where analog fiber-optic transmissions systems, compatible with existing analog transmission technology, are desirable [1]. Examples include the transmission of multiplexed video signals [2]–[4], microwave radio [5], satellite terminals [6], sensory signals, and frequency division multiplexed voice channels [7].

Voice, image, and data transmissions are converging, and the markets are emerging. The first, and perhaps the largest market, is the existing consumer base CATV with its pay-TV, request-TV, and special services subsegments. But the use of interactive video is emerging within large corporation complexes, universities, government sites, and military bases. Beyond these lie sectors such as the "back offices" of stock brokerages, banks, insurance companies, larger hospitals, and real estate offices. The delivery of such bidirectional advanced video, voice, and data services will require a vast bandwidth and that, by definition, requires the use of optical fiber as the medium.

Point-to-point fiber-optic links have proven to have better performance than copper-based media for long haul telephone applications. Data rates in the multigigabits per second range, together with repeaterless operations over several hundred kilometers, have been reported. Fiber-optic media offer many desirable properties over conventional metallic media: high bandwidth, low loss, noise immunity, physical size (weight), potentially low cost, etc. However, fiber optics is not a technology in widespread use today, other than the long haul transmission market, primarily due to relatively high system cost compared to the metallic media-based systems. Presumably, modulators/demodulators (optical transmitters/receivers), analog-to-digital/digital-to-analog converters, time division multiplexers/demultiplexers, etc., are required at the terminals of each fiber end and add considerable cost to a fiber-optic system.

In this paper, characteristics of pulse width modulation (PWM) were studied to explore a potentially cost-effective analog communication alternative in fiber-optic links to the predominantly digital techniques presently used.

II. Motivation to Use PWM

Current state-of-the-art in the intensity-modulation of optical sources, particularly for the light emitting diode (LED), is capable of producing an analog optical signal. However, the analog signal carried by PWM modulation can easily pass through digital logic gates, allowing digitally controlled signal switching by cross-point logic gate arrays. Thus, the PWM modulation can be practical vehicle to mix digital and analog signals into a common switching fabric.

PWM modulation makes sense as an economic alternative to PCM for video signal transport from the remote node to the customer premises link of the local access

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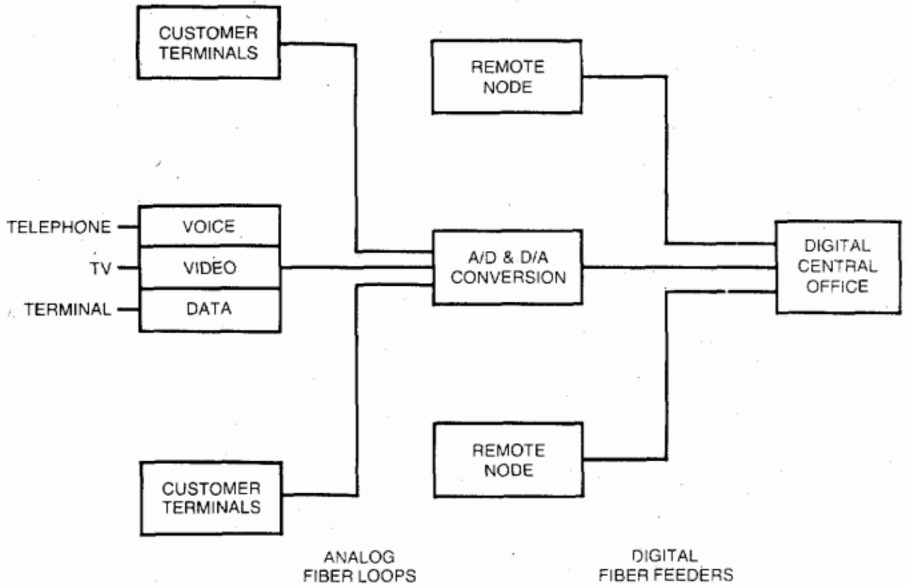


Fig. 1. Wide-band multiservices distribution systems. Fully integrated data/voice/video services by a pair of optical fiber to customer's promise. Information vendors will be able to connect up their trunk line to central office. Central office will provide wide-band switching service.

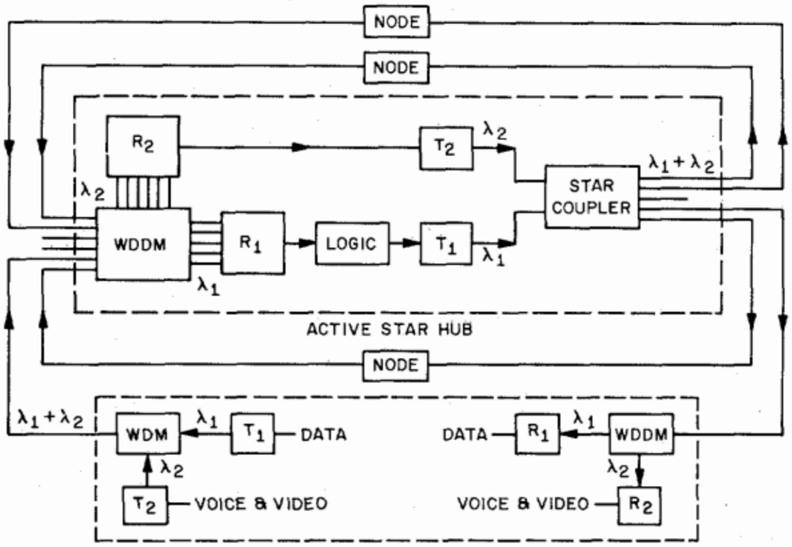


Fig. 2. Active star local area network architecture. λ_1 = short wavelength channel; λ_2 = long wavelength channel. WDM = wavelength division multiplexer. WDDM = wavelength division demultiplexer. T_1, R_1 = short wavelength transmitter and receiver pairs. T_2, R_2 = long wavelength transmitter and receiver pairs. Receivers at the hub can be in individual receiver arrays or a large area photo-detector single receiver.

wideband video/voice/data distribution system illustrated in Fig. 1. However, PCM may be the preferred way for signal transport from the remote node to the central office due to possible jitter accumulations. Of course, this requires a conversion of PCM signal to PWM at the remote terminals. Nevertheless, the use of PWM allows maintenance of the expensive equipment by the service vendor.

Bursty data traffic tends to prefer packet switching technology, while real time voice and video can be handled more easily by circuit switching networks or frequency division multiplexed (FDM) systems. For this reason, the fiber-optic LAN concept shown in Fig. 2 may be well suited for integrated information service by taking advantage of the wavelength division multiplexing capability of lightwave media. A unique characteristic of the topology shown in Fig. 2, and variations thereof, is that it allows us a separate operation of two different kinds of data in a single physical medium. The necessary hardware components, network protocol, etc., are discussed elsewhere [8]. It is sufficient for our purpose to point out here that PWM analog communication techniques can be a vehicle to provide voice and video service in one wavelength channel (say λ_2), while the other wavelength channel (λ_1) can be used to implement a conventional digital data packet switching LAN protocol.

It is also a worthwhile consideration that currently installed base broad-band systems use analog modulation techniques. PWM can provide a suitable interface between these current analog devices to fiber-optic media without making the existing equipment obsolete, at least for the transitional period. This will enable fiber-optic media to penetrate into such a market segment.

In summary, the advantages of digital switching and fiber transport can be realized along with the economies of a simplified modulator and demodulator circuit. PWM circuitry is more cost effective than similar PCM digital circuitry on a per-customer basis at present whenever it is applicable.

III. Pulse Width Modulation

A. Modulation Method

The modulation process itself is well known [9] but, for completeness, we will describe it here briefly. The generation of a pulse width modulated signal requires that the amplitude of the input analog signal be sampled periodically. The sampled amplitude is then converted into a pulse width. The sampling process does not quantize the analog signal as a PCM digital encoder must, but instead, continually varies the output pulse width. For purposes of illustration, Fig. 3 depicts a particular procedure wherein both the leading and trailing edges are modulated. The amplitude of the triangular wave is slightly greater than the peak-to-peak excursion of the signal itself. This method results in a natural sampling in which the message wave varies during the sweeping process, and the length of a width modulated pulse is proportional to the magnitude of the message wave at the pulse edges.

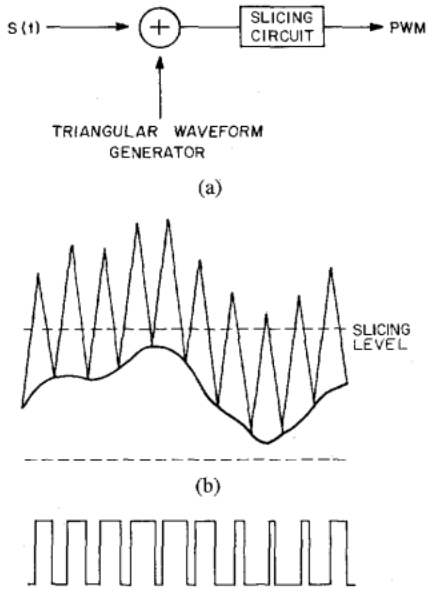


Fig. 3. Generation of pulse width modulated pulses: (a) block diagram, (b) summation of signal and carrier, (c) PWM output.

B. Spectra of PWM Signals

Using a double Fourier series method taken from an unpublished paper by W. R. Bennett, Black [10] arrived at the following series for PWM pulses which were trailing edge modulated by natural samples of a sinusoidal modulating wave:

$$F(t) = \frac{1}{2\pi} S(t) + \sum_{m=1}^{\infty} \frac{\sin(m\omega_s t)}{m\pi} - \sum_{m=1}^{\infty} \sum_{n=-\infty}^{\infty} \frac{J_n(m\pi M)}{m\pi} \cdot \sin\left(m\omega_c t + n\omega_s t - m\pi - \frac{n\pi}{2}\right) \quad (1)$$

where the message signal is

$$S(t) = M\pi \cos(\omega_s t) \quad (2)$$

and the carrier is assumed to be a sawtooth waveform with the repetition rate of $\omega_c/2\pi$. By symmetry argument, the spectra of pulse width modulated pulses with both edges modulated can be obtained easily from (1):

$$M_p(t) = \frac{1}{\pi} S(t) + 4 \sum_{m=1}^{\infty} \sum_{k=0}^{\infty} (-1)^{m+k} \frac{J_{2k+1}(m\pi M)}{m\pi} \times [\cos(m\omega_c t) \cos((2k+1)\omega_s t)]. \quad (3)$$

Equation (3) represents a fundamental advantage of both edge modulated pulses with natural samplings. The harmonic interference (the second term in (1)) is completely suppressed, and all the even order sidebands of the modulated signal around the carrier frequency are also eliminated. This will reduce the crosstalk between adjacent multiplexed channels.

In general, we require

$$\omega_c \geq 2\omega_s \quad (4)$$

to faithfully reproduce the original signal. Therefore, PWM will be free from intermodulation as long as the Fourier components of $(\omega_c - n\omega_s)$ in (3) are negligible for $n > 3$. The conditions will be easily met if the modulation index M is small, since higher order Bessel functions vanish for small arguments. For a multichannel system, M is inevitably small so that the interference of the intermodulation products with the baseband signal will be small. It should be noted, however, that as M decreases, the signal-to-noise ratio SNR will proportionally suffer.

It is interesting to compare (3) with typical frequency modulated (FM) signal spectra:

$$M_f(t) = \text{const} \sum_{n=-\infty}^{\infty} J_n\left(\frac{\Delta\omega_c}{\omega_s}\right) \cos\left[(\omega_c + n\omega_s)t + \frac{n\pi}{2}\right]. \quad (5)$$

As anticipated, there exists a considerable similarity between (3) and (5). It should be noted, however, that (5) contains the even order sidebands of the modulated signal around the carrier frequency, while they are missing in

(3). It can be shown that pulse frequency modulation (PFM) may contain even more complicated spectra than (5) implies, and may be more prone to the crosstalk than conventional FM. By choosing ω_c very high, the baseband signal $M\pi \cos(\omega_s t)$ in (3) can almost always be separated from the unwanted sidebands signals (the second term in (3)). On the contrary, the suppression of sidebands in FM can only be achieved by reducing the modulation index $(\Delta\omega_c/\omega_s)$. Unfortunately, such a narrowband FM signal does not provide an FM advantage of SNR. Thus, for larger multichannel systems, the PFM technique is less attractive.

C. Demodulation Method

By far the most common scheme for extracting the signal from PWM pulses is to use low-pass filter. An ideal filter has a very sharp cutoff characteristic at frequencies above $\omega_s/2\pi$ as implied by (3). For multiple signal sources such as voice video and data, the signals are first frequency division multiplexed electronically. The resulting signal is then modulated by PWM. A series of bandpass filters is connected to the output of the receiver. Each filter serves as both demodulator and demultiplexer of the wanted signal.

D. SNR of PWM Signals

Even when the noise is small compared with the wanted signal, the noise manifests itself as time jitter in the leading and trailing edges of the recovered pulses. Thus, there exists a direct relationship between time jitter and ultimate SNR in the PWM signals.

Fig. 4(a) shows how a small noise voltage (N_t), when superimposed on a PWM pulse of peak value of S_t, acts to change the slicer triggering time by an amount ϵ.

From the geometry of the figure

$$\frac{S_t}{N_t} = \frac{T_{\min}}{\epsilon} \tag{6}$$

where $T_{\min}$ is the minimum pulse width which can be produced by the transmitter. When the PWM signal is transmitted to the receiver, the error in timing ϵ will cause a noise voltage N_0 in the output of the low-pass filter. When the pulses are modulated fully by a test signal which has a uniform amplitude probability distribution, the corresponding rms pulse width displacement $\langle S \rangle_{\text{rms}}$ approaches

$$\langle S \rangle_{\text{rms}}^2 = \frac{2}{\Delta T}\int_{-\Delta T/2}^{\Delta T/2} t^2\, dt = \frac{\Delta T^2}{6} \tag{7}$$

where ΔT is the maximum pulse width excursion shown in Fig. 4(b). In deriving (7), we have assumed symmetric pulses for simplicity. This is a more conservative signal intensity estimation than a conventional single tone sine wave test signal. If S_0 denotes the corresponding rms signal voltage in the output of a low-pass filter

$$S_0 = C\frac{\Delta T}{\sqrt{6}} \tag{8}$$

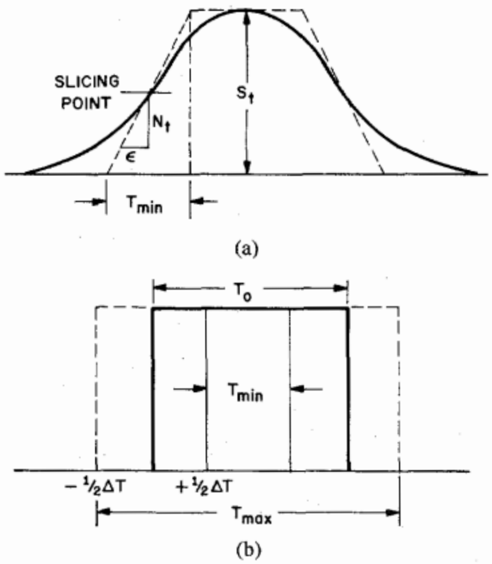


Fig. 4. *S/N* considerations in PWM pulses. (a) relation between time jitter and noise; (b) maximum exclusion of PWM signal from its unmodulated position (T_0). For the sake of brevity, square pulse waveforms are drawn.

where C is a constant. Similarly, N_0 can be expressed as

$$N_0 = C\frac{N_t}{S_t T_{\min}}. \tag{9}$$

Hence, we have

$$\frac{S}{N} = 2\frac{S_0}{N_0} = \frac{S_t}{N_t}\sqrt{\frac{2}{3}}\left[\frac{B_t}{B_c} - 1\right] \tag{10}$$

where S/N is the SNR of the message waveform, $B_t (= 1/T_{\min})$ is the bandwidth of the transmitter, and B_c is the bandwidth of the carrier. It has been implicitly assumed that the bandwidth of the message waveform is $B_c/2$. The relationship shown in (10) illustrates a general principle common to all pulse systems: namely, that the rms SNR at the output is approximately proportional to the ratio of the total bandwidth gainfully used to the signal bandwidth.

A more useful relationship can be obtained by combining (6) and (10)

$$\frac{S}{N} = \sqrt{\frac{2}{3}}\left[\frac{1}{B_c} - \frac{1}{B_t}\right]\left(\frac{1}{\epsilon}\right). \tag{11}$$

A typical multimode short wavelength laser transmitter designed for a 90-Mbit/s system has a B_t of 180 MHz and an ϵ of 50 ps [11]. If we choose a 45 MHz carrier, 46 dB of SNR can be achieved. It should be emphasized here that the SNR in (11) is a wide band SNR.

E. Modulation With Sine Wave Carrier

For small signals relative to the carrier p–p amplitude, a sine wave may be used as a carrier source, since $\sin\theta \approx \theta$ for small θ. It is also conceivable that the amplitude distortion can be easily calculated given the fact that the pulse width change is proportional to $\sin^{-1}(V_{in}/V_c)$ for a sine wave carrier with p–p voltage V_c and an input signal with p–p voltage V_{in} and, given that the output voltage V_o after demodulation, (i.e., pass-through the low-pass filter) is proportional to the pulse width variations, i.e.

$$V_o = C \sin^{-1}\left(\frac{V_{in}}{V_c}\right) \tag{12}$$

where V_{in}/V_c can be interpreted as a modulation index. If we define a relative instantaneous amplitude distortion $\Psi(t)$ by

$$\Psi(t) \equiv \left|\frac{\overline{V}_0(t) - V_0(t)}{\overline{V}_0(t)}\right| \tag{13}$$

where $\overline{V}_0(t)$ is the expected distortion-free output voltage, then the amplitude distortion caused by the sine wave carrier can be obtained easily:

$$\Psi = \frac{\sin^{-1} M}{M} - 1. \tag{14}$$

F. Multiplexing Scheme

Both frequency division multiplexing (FDM) and time division multiplexing (TDM) can be implemented within the framework of PWM modulated optical communication channels. Since these techniques are well known and fully described in many communication text books, we will omit our discussion on these subjects.

IV. Fiber-Optic Analog Signal Transmission Experiment

A. Simple Analog Signal Transmission

Fig. 5 shows the experiment setup used to test the analog transmission capability of optical fiber using the PWM technique. In order to separate high-order harmonics of an analog baseband signal from the carrier sidebands, the carrier frequency (50 MHz) was chosen much higher than test signals (5 MHz). In this experiment, a HP-8640B sine wave generator and a Tektronix FG-504 function generator were used as carrier and signal sources, respectively. The carrier voltage input to the adder circuit was 1 V p–p and the signal voltage level was limited to 0.2 V p–p to avoid the nonlinearity associated with the sine wave carrier. As shown in Fig. 6, both the triangular and square wave test signals were reproduced with little distortion. The corners and peaks were probably rounded off by the low-pass filter (BW = 20 MHz).

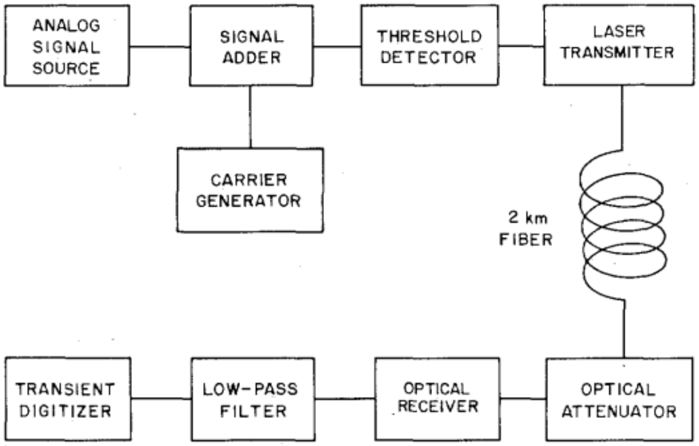


Fig. 5. Block diagram of optical analog signal transmission experimental system. Analog signal source; VP-1000 Pioneer laser disk player and Tektronix FG-504 function generator. Carrier generator; Hewlett-Packard HP-8640B sine wave generator and Tektronix FG-504 function generator for triangular carrier. Signal adder; Passive resistor network. Threshold detector; Hewlett-Packard HP-8082A pulse generator, using external width control mode. Laser transmitter; Designed for 90-Mbit/s long-haul multimode transmission system (AT&T). It can produce over 400 Mbit/s pulses. Fiber; 62.5/120-μm loop feeder fiber (AT&T). Optical attenuator: Photodyne 1950XR continuously variable optical attenuator. Optical receiver; Optical receiver designed for long-haul transmission system (AT&T), bandwidth 25 MHz. Low-pass filter; optical receiver itself acts as a low pass filter. Additional filtering was done by the plug-in amplifiers of Tektronix 7904 oscilloscope (20 MHz Bandwidth), if necessary. Transient digitizer; Tektronix 7912 AD transient digitizer with 4052A waveform processor.

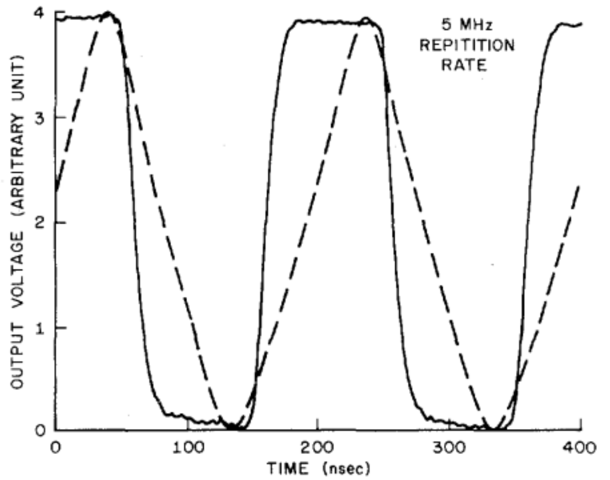


Fig. 6. Examples of analog signal transmission by PWM. Signal source; Hewlett-Packard HP-8082A function generator. Carrier source: Hewlett-Packard HP-8640B sine wave generator. Modulation index was maintained at less than 10 percent to reduce distortion caused by the sine wave carrier. Single shot waveforms are captured by Tektronix 7912AD transient digitizer.

B. Linear Dynamic Range

Another important consideration in analog signal transmission is the linear dynamic range of the communications system. It was measured using a 1.0-V p–p triangular waveform (40-MHz repetition rate) obtained from a Tektronix FG-504 function generator as a carrier signal and a continuously varying 1.6-MHz sine wave from a HP-8640B as a test signal. An almost constant ratio between the input test signals and output signals at the low-pass filter was observed as long as the p–p input signal was less than 0.95 V and greater than 0.0025 V. This represents a linear dynamic range of 51.6 dB. The output signal waveforms at both extremes are plotted in Fig. 7. Test signals between 0.95 and 1.0 V displayed an apparent distortion, probably due to the rounded peaks of the triangular carrier waveform. At the lower input signal end, the SNR was the limiting factor, particularly carrier leakage. The dynamic range could be further extended by using a better low-pass filter.

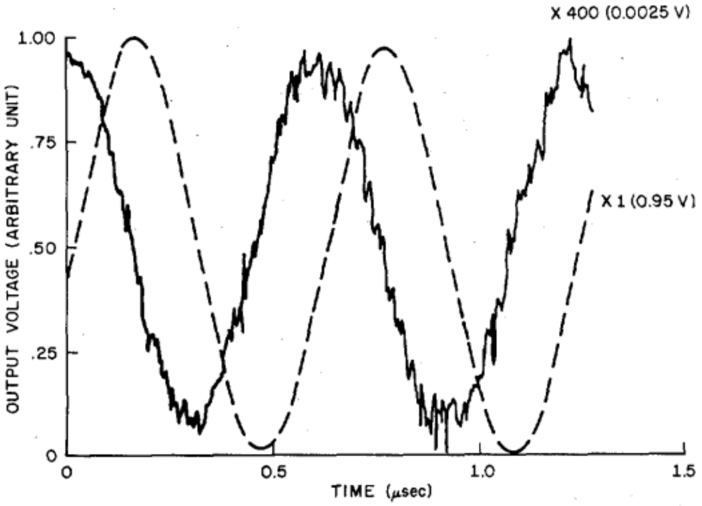


Fig. 7. Dynamic range of PWM analog signal. Signal source; Hewlett-Packard HP-8640B sine wave generator. Carrier source; Hewlett-Packard HP-8082A function generator. Triangular carrier was used to minimize signal distortion. Single shot waveforms are captured by Tektronix 7912AD transient digitizer.

C. Baseband Video Signal Transmission

The experimental setup used to demonstrate a video link is identical to that shown in Fig. 5, except that the signal source, low-pass filter, and transient digitizer were replaced by VP-1000 video disk player (Pioneer), CLC104A1 linear amplifier (ComLinear), and CVM-1250 TV monitor (Sony), respectively. The baseband video signal (1 V p–p), a still video frame (typical movie scene) obtained from a commercial video disk player, was modulated by PWM using a 1.5-V p–p, 15-MHz triangular waveform carrier. As shown in Fig. 8, there was no noticeable picture quality degradation in the video link (2-km fiber plus 6-dB attenuation) compared to the direct connection between the video disk player and the TV monitor. When the carrier frequency was varied from 8 MHz to 50 MHz, again the picture quality was not affected. For carriers below 8 MHz, some alterations of colors, as well as contrast, began to appear; and for carriers below 5 MHz, the picture quality was totally unacceptable. However, the minor degradations cannot be seen in the photographed picture. This may be due to the fact that the exposure time used to take the picture was 1 s, which is effectively a signal averaging. It is worthwhile to mention here that there exists an observable difference when a sine wave carrier was used in place of a triangular wave. Nevertheless, the picture quality was entirely acceptable. For the same reason mentioned above, the difference did not show up in the photographed pictures. In future work, standard video measurements should be provided to allow quantitative judgment as to applicability for CATV, video conferencing, graphics, etc. In this paper, we will merely demonstrate the feasibility by simple power spectra measurements.

Fig. 9(a) shows the power spectrum of the unmodulated NTSC baseband video signal and a single-tone test signal at 10 MHz obtained by HP-8557A spectrum analyzer. It is virtually identical to that of the same signal modulated by PWM, transmitted through the fiber link, and followed by detection at the receiver within a dc to 20-MHz spectral window. The carrier was a 40-MHz triangular wave and the modulation index was about 80 percent. When the carrier frequency was reduced to 15 MHz while maintaining the same modulation index, the sidebands around the carrier frequency predicted by (3) appeared within the 20-MHz window, as shown in Fig. 9(b). In this experiment, the 10-MHz test signal was removed. It is interesting to note that, when the carrier was replaced by a sine wave of the same amplitude, the intensity of the sidebands was diminished (Fig. 9(c)). At the same time, the signal intensity was also considerably reduced. This may be explained by the fact that the slope of a sine wave near the zero crossing is somewhat higher than that of a triangular wave. This results in an effective reduction of the modulation index which, in turn, results in a suppression of the sidebands as expected from (3).

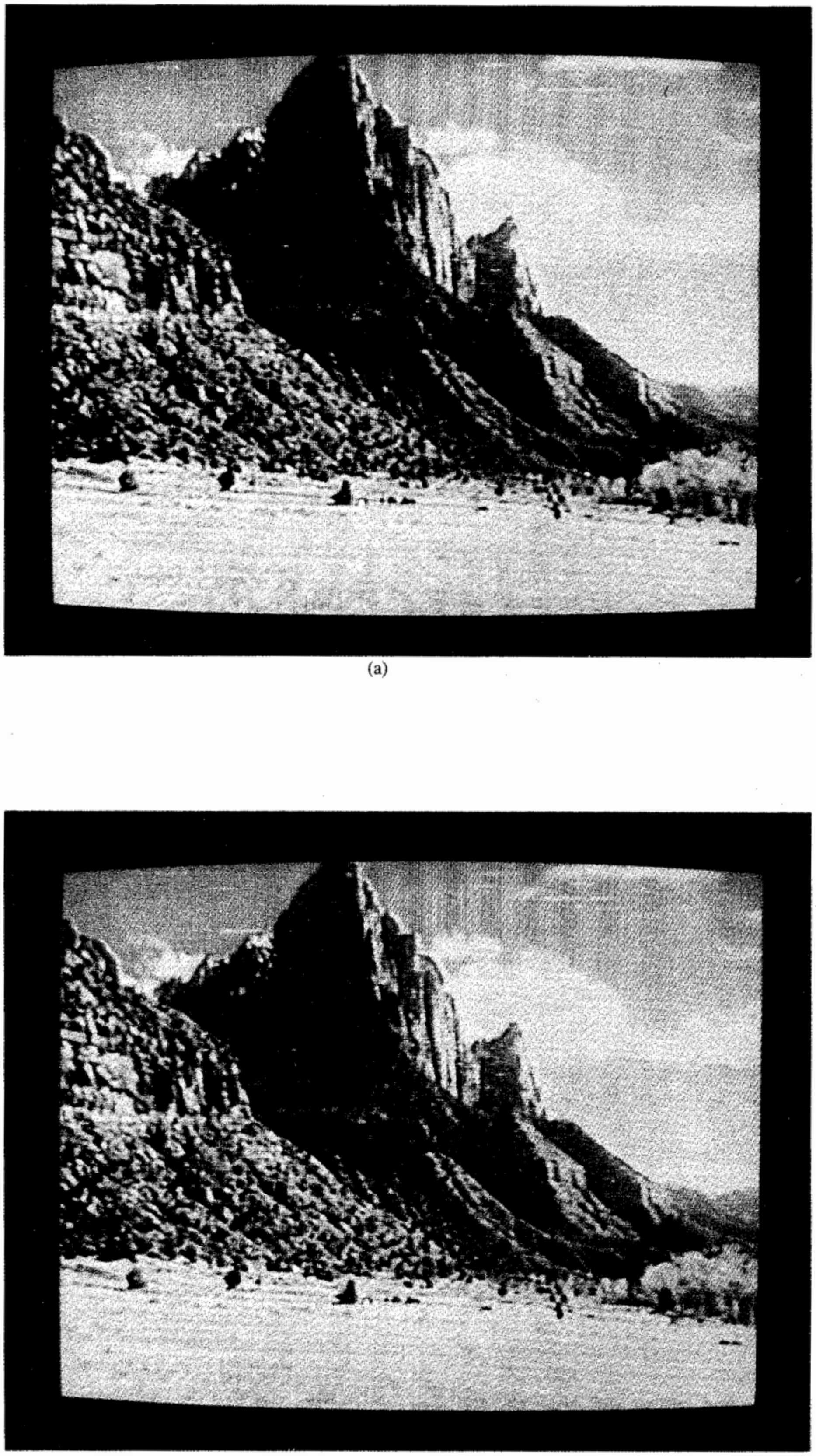
D. RF Video Signal Transmission

In the consumer-oriented CATV application, the subscriber premises equipment cost is the most critical issue. One of the most cost effective approaches would be the transmission of RF video signals using standard airway broadcasting TV channels so that the customers can connect the optical receiver output directly to their TV sets. Using the identical experimental setup as the PWM baseband video transmission, a PWM RF video signal (CH 3) was transmitted through fiber. The received RF video signal, without bandpass filter, was fed directly into the TV monitor. The TV tuner itself was acting as the bandpass filter. The picture quality was almost as good as direct connection, but a slight distortion of the sound was noted. The carrier was a 0.5-V p–p 185-MHz sine wave, and the video RF signal (10 mV p–p) was amplified by a wideband RF amplifier (HP-8447F) to about 0.25 V p–p.

The power spectrum of the received signal shown in Fig. 10(a) is identical to that of the direct RF signal from the video disk player (figure not shown). When the RF input signal was attenuated by about 22 dB, two extra spectrum components appeared as indicated by two arrows in the same figure (Fig. 10(b)). Nevertheless, the picture quality remained very good, as expected, since the TV tuner does not use the lower sideband of the video signal. It should be noted here that the actual NTSC video format requires a partial suppression of the lower sideband of the video signal. When the RF video signal was further reduced, say more than 26 dB, a large number of spectral peaks appeared in the power spectrum and the picture quality became poor. The additional peaks originated from the carrier itself. Fig. 10(c) shows the power spectrum of the carrier. This clearly demonstrates that SNR was limited by the purity of our carrier generator and not by the fiber link or modulation method.

E. Multichannel RF Video Signal Transmission

With a carrier frequency of 185 MHz, the useful signal bandwidth is about 90 MHz. This allows multiplexing of TV channels 2–6 (54–88 MHz). Any wide band optical



(a)

(b)

Fig. 8. Photograph of TV monitor. (a) Direct connection. (b) 2-km video link +6 attenuation with 15-MHz triangular carrier. The optical receiver sensitivity limit was not reached. The attenuation of 6 dB was necessary to adjust output baseband video signal level to NTSC format (1 V p–p) due to a very high gain in the optical receiver.

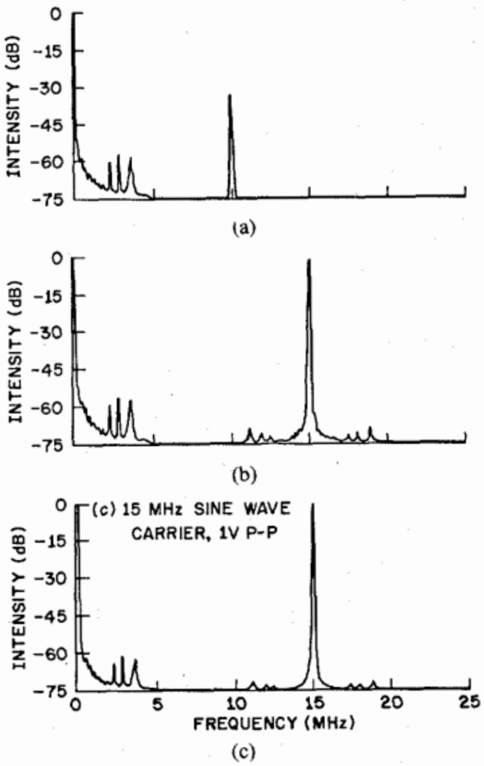


Fig. 9. Power spectrum of PWM modulated NTSC baseband video signal at 30-KHz resolution bandwidth. (a) Baseband video signal plus 10-MHz single-tone test signal. (b) The video signal was modulated by 15-MHz triangular waveform carrier. (c) Same as (b), except the carrier waveform was replaced by sine wave. Power spectra were taken by Hewlett-Packard HP-8557A spectrum analyzer.

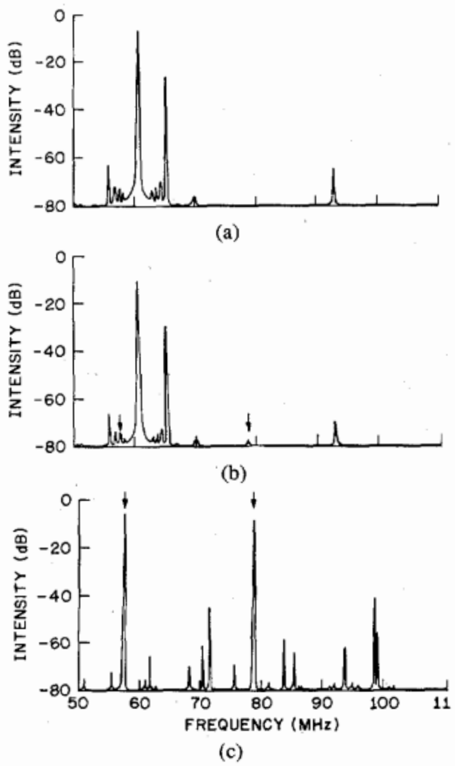


Fig. 10. Power spectrum of PWM modulated RF video signal. (a) PWM modulated RF video signal with 48-dB gain. (b) Same as (a), but with 26 dB gain. Lines indicated by arrows represent the components originating from the carrier. (c) Power spectrum of carrier wave itself.

receiver (dc–90 MHz) with a moderate gain would be sufficient, since the TV tuner will provide enough gain, as well as automatic gain control (AGC) in addition to the channel selection function (effective bandpass filter). To illustrate this point, both the RF outputs of the video disk player (CH 4) and a video cassette recorder (CH 3) were added together after suppression of the lower sideband and sent the resultant signal through the fiber link. The fiber link faithfully regenerated both video signals. Again, a quantitative video signal measurement should be done in the future.

As the number of video channels increases, in general the probability of crosstalk between channels proportionally increases. In the PWM scheme, the strongest source of the crosstalk is the third harmonic lower sideband term ($k = 1$) in (3). Thus, for all practical purposes (3) can be rewritten as:

$$M_p(t) = \frac{1}{\pi} S(t) + 2 \frac{J_3(\pi M)}{\pi} \cos [(\omega_c - 3\omega_s t)] \quad (15)$$

for the frequency components within the receiver bandwidth. Using (2) and (15), the power ratio (γ) of the signal to the third harmonic interference term can be calculated as

$$\gamma = \left[\frac{J_3(\pi M)}{\pi M/2} \right]^2. \quad (16)$$

For small M, γ decreases very rapidly, as shown in Fig. 11. Even at 90-percent modulation, γ (expected crosstalk) is less than -55 dB.

In deriving (3) from (1), it was assumed that carrier waveform is a perfect triangular shape. For a nonideal triangular carrier, all terms appearing in (1) would be presented in PWM modulated signal. Because of this, it is expected that harmonic interference may arise from the second term in (1). Therefore, a nonideal carrier waveform could generate intermodulation products within the signal bandwidth. Thus, a generation of pure triangular waveforms dictates the successful implementation of the multichannel video signal transmission by a PWM technique.

F. Integration of Voice Video and Data

The concept of local area networks (LAN's) is well developed in the field of digital computing and data communication. LAN's are mainly used for sharing computing resources and exchanging data among a number of users in a limited geographic span. Adding real time voice and video capability to these networks makes them very attractive for the office information systems of the future, including hospital and clinical information systems and automated factory floors.

For the purpose of demonstration, the following three types of signals were multiplexed by simply adding them together, followed by PWM modulation, and sent through the fiber link:

1) $2^{23} - 1$ bits long, 5 Mbit/s psuedorandom NRZ data pattern obtained from Tautron BERT-325C data generator,

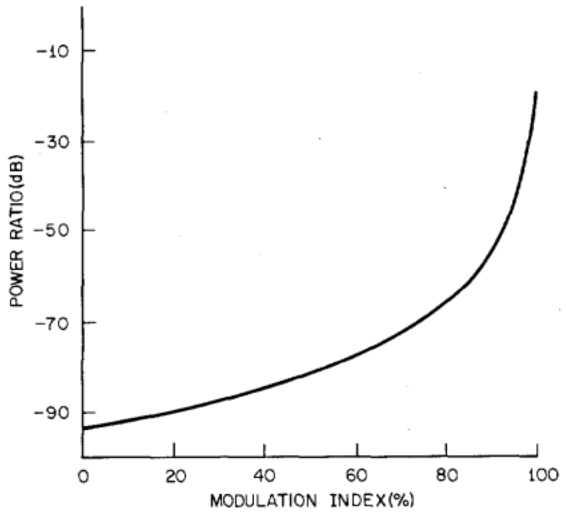


Fig. 11. Power ratio between baseband signal and the third harmonics.

2) An FM modulated (10.7-MHz carrier) audio signal, and
3) RF video signal (CH 3) obtained from the video disk player.

Fig. 12 shows the audio modulator and demodulator used in this experiment. The 1648 type of voltage controlled oscillator (VCO) is used in conjunction with a tank circuit to set the frequency of operation and a variactor diode to modulate the tank's capacitor value and, hence, the frequency deviation was limited to ± 75 kHz. The sound demodulator uses a readily available 10.7-MHz ceramic filter to limit the bandwidth of the sound carrier, a preamplifier, and a phase-locked loop running at 10.7 MHz.

The following is the summary of the test results:

1) BER of less than 10^{-9} in the digital data channel,
2) over 60-dB SNR at 10-kHz BW on the audio channel, audio frequency ranging from 100 Hz to 10 kHz, and
3) no visible degradation in the video quality.

The length of the optical fiber used in this experiment was about 2 km. The experimental evidence presented here showed the feasibility for the integration of the bursty digital data, and real time voice and video information into a single medium by PWM. As mentioned in Section II, however, PWM in combination with the WDM capability of fiber-optic technology may provide a more cost effective means to achieving the integration.

V. Comparison Between PWM and PFM

It is conceivable that PFM technique could provide a similar analog transmission capability. However, there exists one major difference in that the information is carried by the base-band components in PWM, while it is contained in the sidebands of the carrier in PFM. Thus, the transmission of carrier is not necessary for PWM, resulting in a much wider usable bandwidth.

In order to demonstrate this point, a PFM modulator/demodulator described in open literature was built and compared with the PWM system. Fig. 13 illustrates the block diagram of the PFM system used in this experiment. The modulator uses a voltage controlled multivibrator (F11C58 Fairchild Emitter-Coupled Oscillator). The frequency control is accomplished with voltage variable current sources that control the slew rate of a single external timing capacitor. The maximum frequency capability is 150 MHz. In order to ensure the linearity of the modulation, the input video signal was attenuated to limit its peak-to-peak swing within 0.4 V. The demodulation was achieved by generating fixed width pulses on both trailing and leading edges of the input signal. This was accomplished by delaying the input signal two ECL gates delay (approximately 6-ns) and exclusive ORing the delayed signal with the undelayed signal resulting in a train of fixed width pulses (~ 6 ns of the gates delay) that occur at each input signal transition. As the frequency of the input signal increases, the number of fixed width pulses increases as does the average voltage level. The resulting PFM signal has baseband components. A lowpass filter removes everything but the baseband signal, which is amplified to standard voltage (1 V p-p) and impedance (75 Ω) levels. The circuitry for this PFM scheme is simple and straightforward; still, the number of parts counts is considerably greater than that needed for PWM.

Using a short wavelength (0.87 μm) LED based optical data link transmitter designed for 50 Mbit/s operation, an NTSC video signal obtained from video disk player was transmitted through fiber. In up to 1 km fiber link length, no obvious difference in the reproduced video picture quality between the two modulation techniques was observed. However, as the link distance increased beyond 1 km, no degradation in the video picture quality was observed for PWM link, while a severe degradation in the picture quality was noted in the PFM link. The linear front end preamplifier output signal of the optical receiver showed the severe degradation in the rise time of the pulses. This may explain the poor performance of the PFM video link, since the pulse train is sensitive to crosstalk and noise ingress during the transition time when the signal is passing through the linear portion of the circuit transfer characteristic. When the link distance increased over 3 km, the signal was completely lost in the PFM system, while the PWM system still showed little sign of the degradation. This result can be explained by the fact that the graded index multimode fiber (62.5/120 μm, AT&T loop feeder fiber) bandwidth is limited to about 25 MHz $\cdot$ km due to chromic dispersion of LED. In order to confirm it, after the optical source was replaced by a laser transmitter, all of the above experiments were repeated. As expected, no performance difference between PFM and PWM was noted.

The effect of the carrier frequency on the modulation of the video signal was studied using the 1-km fiber link and the LED transmitter. Carrier frequency was varied from 10 MHz to the absolute upper attainable frequency (100 MHz) from the transmitter. For the PWM system, the

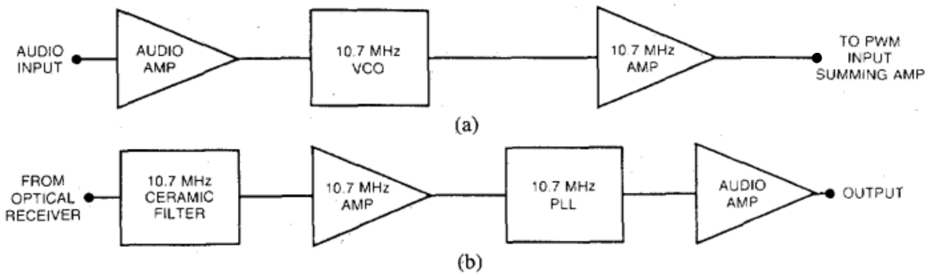


Fig. 12. (a) Audio modulator and (b) demodulator.

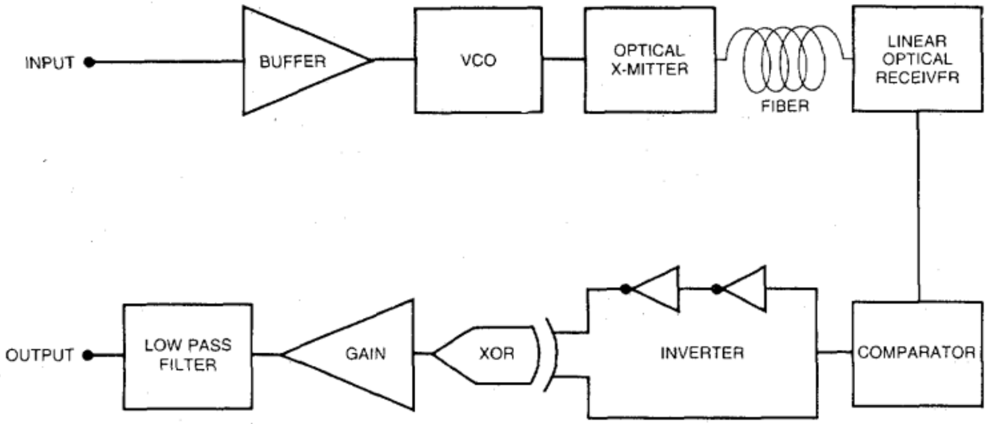


Fig. 13. Block diagram of experimental video link.

video signal was not affected by the carrier frequency. However, it was found that the quality of the video picture was dependent on the choice of the carrier frequency for the PFM system, probably due to its effect on the phase of the color subcarrier. An analysis of intermodulation products in the video disk player system by DeHaan [12] also predicted that a judicious choice of the frequencies of the luminance, color, and sound components of the recorded signal was necessary to obtain TV pictures of good quality. Thus multichannel PFM may become increasingly more difficult as the number of video channels increases. For a carrier frequency above 50 MHz, the PFM scheme did not work due to an inability to transmit the carrier through the fiber link.

The experimental evidence presented here clearly demonstrated that the PWM method is preferable over PFM for a multichannel analog transmission system. Another important practical advantage is that the LED based PWM method is still useful, even when the link distance spans several kilometers. For the same reason, PWM can provide a high-resolution video transmission capability in LED based fiber-optic links. It should be noted, however, that the multichannel capability (i.e., wide bandwidth) of PWM readily vanishes with the nonsymmetric carrier, such as the more commonly used sawtooth waveform, due to harmonic interference arising from the second term in (1). Pure analog video is very susceptible to the ravages of crosstalk, distortion, and noise ingress. Because of the baseband nature of the PWM signal, it is expected that a similar noise problem may be encountered as it passes through a large scale digital switching fabric. Therefore, PWM may be well suited for a point-to-point signal transport and a small scale switching system.

VI. Discussion

The analysis of the PWM signal revealed that the use of a PWM provides a simple, straightforward method of converting an analog signal into a digital-like pulse train, and of subsequently receiving the baseband signal. When a uniform sampling is used, the resulting PWM signal contains not only the wanted message wave, but its harmonics—with natural sampling, these harmonics are missing. This would lead one to expect a net deterioration of signal fidelity when the sampling is uniform instead of natural. This explains why our earlier unpublished results on PWM video link experiments, using a sawtooth waveform as a carrier, showed a severe intermodulation problem and were totally unacceptable for fiber-optic video link application. When the sawtooth waveform carrier was replaced by a triangular waveform carrier, the intermodulation interference problem disappeared. By modulating both leading and trailing edges with a symmetrical triangular waveform carrier, a natural sampling can be accomplished, and thus, virtually all of the potential interfering Fourier components in the modulated signal are eliminated. No evidence of the existence of the intermodulation products was observed when a symmetric triangular carrier was used.

A linear dynamic range of more than 51.6 dB was experimentally observed in the analog signal. The leakage of the carrier components through the low pass filter used in the experiment was the main source of noise. It has also been noted that any low frequency components of the carrier itself could interfere with the baseband signal. Data presented in this work are somewhat qualitative, and a more careful SNR study should be conducted to take full advantage of the analog transmission capability of PWM techniques in fiber-optic communication links.

The intermodulation-free characteristic of PWM makes it a very attractive vehicle to implement broad-band service in fiber optic links. Applications may include low-cost video links in fiber-optic subscriber loop systems and service integrated optical broadband communication systems, such as hospital and clinical information systems, factory automation, etc. However, it should be mentioned here that the PWM signal is fundamentally analog in nature. Thus it is susceptible to crosstalk, noise, power-supply rejection, etc. This may severely limit the use of PWM to a relatively small and compact sized network. On the other hand, in the broad-band LAN application shown in Fig. 2, network protocol will control the usage of the channel in such a way that a particular channel will be available to a specified node at a given time. This could alleviate the noise problem mentioned above.

The more widely publicized PFM [13], [14] technique also provides an analog capability in fiber-optic links. For a single channel link, the SNR advantage of PFM may be a more attractive alternative than PWM for a relatively large scale system, whenever its use is permitted. However, PWM allows the use of the fiber bandwidth more efficiently. This is particularly important when an LED is used as an optical source, since the chromic dispersion generally limits the fiber bandwidth length product to about 20–25 MHz · km for a short wavelength LED based system. For example, a high resolution video signal requires a modulation carrier frequency considerably higher than 25 MHz. Thus, a PFM system cannot be used for the high resolution video signal transport through the long fiber-optic link, while this limitation does not apply for the PWM system.

One of the serious drawbacks of the analog technique, whether PFM or PWM, is that it does not allow noise-free regeneration of the signal in cases where repeaters are required. Thus, the PCM may remain the modulation technique that is chosen in many fiber-optic links. Finally, it should be emphasized here that our goal was to demonstrate PWM's feasibility and to suggest applications for its use in fiber-optic links. The true merit of PWM should be critically reevaluated to determine its usefulness in the wide range of applications from a consumer-oriented subscriber loop plant [15], [16] to sophisticated industrial data services, i.e., fully integrated voice/video/data service LAN's for the offices [17], hospitals [18], [19], and automated factories [20], [21] of the future.

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References

[1] E. E. Basch and H. A. Carnes, "Analog optical communications," in *Fiber Optics*, J. C. Daly, Ed. Boca Raton, FL: CRC, 1984, pp. 181–194.

[2] J. Fox, D. I. Fordham, R. Wood, and D. J. Ahern, "Initial experience with the Milton Keynes optical fiber cable TV trial," *IEEE Trans. Commun.*, vol. COM-30, no. 9, pp. 2155–2162, 1982.

[3] H. Buenning, H. W. Kreutzer, and F. Schmidt, "Subscriber stations in service integrated optical broad-band communication systems," *IEEE Trans. Commun.*, vol. COM-30, no. 9, pp. 2163–2171, 1982.

[4] K. Asatani, R. Watanabe, K. Nosu, T. Matsumoto, and F. Nihei, "A field trial of fiber-optic subscriber loop systems utilizing wavelength division multiplexers," *IEEE Trans. Commun.*, vol. COM-30, no. 9, pp. 2172–2184, 1982.

[5] J. J. Pan, "5 GHz wideband fiber-optic link," in *Tech. Dig. Topical Meet. Optical Fiber Communications* (New Orleans, LA), Feb. 28–Mar. 2, 1983, pp. 74–76.

[6] A. Albanese and H. F. Lenzing, "IF lightwave entrance links for satellite earth stations," in *ICC '79 Conf. Rec.*, vol. 1, no. 1.7.1, 1979.

[7] F. R. McDevitt, N. Hamilton-Piercy, and D. F. Hemmings, "Optimized designs for fiber-optic cable television system," *IEEE Trans. Cable Television*, vol. CATV-2, p. 169, 1977.

[8] S. Y. Suh, A. J. Lumsdaine, S. W. Granlund, D. A. Snyder, S. J. Wetzel, C. J. Danniels, and K. W. Haag, "Active star coupler based fiber-optic local area network," Submitted for publication.

[9] P. F. Panter, *Modulation, Noise, and Spectral Analysis*. New York: McGraw-Hill, 1965, p. 577.

[10] H. S. Black, *Modulation Theory*. New York: Van Nostrand, 1953, pp. 262–281.

[11] S. Y. Suh, "Statistical characterization of digital communication channels," *IEEE Trans. Instr. Measurement*, vol. IM-35, no. 3, pp. 318–323, Sept. 1986.

[12] M. R. DeHaan and C. H. F. Velzel, "Intermodulation and Moiré effects in optical video recording," *Philips Res. Reps.*, vol. 32, pp. 436–459, 1977.

[13] K.-I. Sato, S. Aoyagi, and T. Kitami, "Fiber optic analog–digital hybrid signal transmission employing frequency modulation," *IEEE Trans. Commun.*, vol. COM-33, no. 5, pp. 433–441, May 1985.

[14] K.-I. Sato, S. Aoyagi, and T. Kitami, "Fiber-optic video transmission employing square wave frequency modulation," *IEEE Trans. Commun.*, vol. COM-33, no. 5, pp. 417–424, May 1985.

[15] D. B. Watson, "Application consideration of a fiber-optic video link," *SPIE Proc. Fiber-Optic Technology '82*, vol. 326, pp. 9–13, Jan. 28–29, 1983.

[16] J. W. Lange, "Towards a general integrated broad-band optical fiber telecommunications network in the subscriber area," *SPIE Proc. Optical Fibers in Broad-band Networks, Instrumentation, and Urban and Industrial Environment*, vol. 403, pp. 79–86, May 16–19, 1983.

[17] J. R. Fox, "Studies for a future wide-band local network," in *2nd Int. Conf. Telcommun. Trans.* (London, England), Mar. 1981, p. 221.

[18] S. G. Tolchin and S. A. Khan, "A distributed hospital information system," in *4th Jerusalem Conf. Information Technology: Next Decade in Information Technology*, May 21–25, 1984, p. 620.

[19] S. G. Tolchin, R. L. Stewart, S. A. Khan, E. S. Bergen, G. P. Gafke, P. W. Simborg, M. G. Chadwick, and Q. E. Whiting-O'Keefe, "A prototype generalized network technology for hospitals: Initial implementation," in *Proc. 15th Hawaii Int. Conf. System Science*, 1982.

[20] P. Cleaveland, "Local area networks for industrial control," *I&CS*, pp. 31–37, Aug. 1984.

[21] C. J. Georgopoulos and C. S. Koukourlis, "Fiber-optic link design considerations for applications in noisy industrial environments," *IEEE Trans. Ind. Elec.*, vol. IE-31, no. 3, pp. 209–215, Aug. 1984.

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