TRANSMISSION OF HIGH-SPEED PCM SIGNALS ON CATV SYSTEMS

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INTRODUCTION

This paper describes experimental work conducted at GTE Lenkurt, San Carlos, California, and at GTE Sylvania CATV Equipment and Installation Operation, El Paso, Texas, to examine the feasibility of transmitting high-speed, pulse code modulation signals simultaneously with normal video transmission over CATV systems.

BACKGROUND

Pulse code modulation (PCM) involves the transformation of continuously variable, analog signals into a series of digitally-coded pulses and then reversing this process to recover the original waveform.

The basic PCM system now in service for telephone communications, and used for this experimental study, provides 24, two-way voice channels on two cable pairs, one for each direction of transmission. These channels are processed into a bipolar 1.544 Mb/s digital line format in three successive operations, as shown in Figure 1: sampling; quantizing and encoding.[1] First, a time varying voltage, such as speech (or a sine wave as shown), is converted into discrete samples at a rate which is at least twice the highest frequency to be transmitted. This is defined as pulse amplitude modulation (PAM). Each channel, which has an upper frequency limit of 3400 Hz, is then sampled at 8 KHz to satisfy the sampling rate requirement.

Next, the voltage amplitude of each sample is assigned to the nearest value of a set of discrete voltages. This process is known as quantizing and is equivalent, in mathematics, to rounding off to the nearest whole number or integer. The final step is to code each discrete amplitude value into a binary digital word, similar to coding the letters of the alphabet for telegraphy. Each amplitude sample is coded into an 8-bit digital word and transmitted sequentially (time multiplexed) as a single bit-stream. At the receiver the reverse process takes place, as also shown in Figure 1.

One sampling period for all 24 channels consists of 192 bits (one 8-bit word for each of 24 channels) plus one bit for framing, giving a total of 193 bits. At the 8000 Hz sampling rate, this equals the line rate of 1.544 Mb/s (8000 samples/second x 193 bits). The resultant binary pulses are then in fixed, predetermined time positions, and only the presence or absence of a pulse determines the information content of the signal. This type of 24-channel system is designated as T1 carrier.

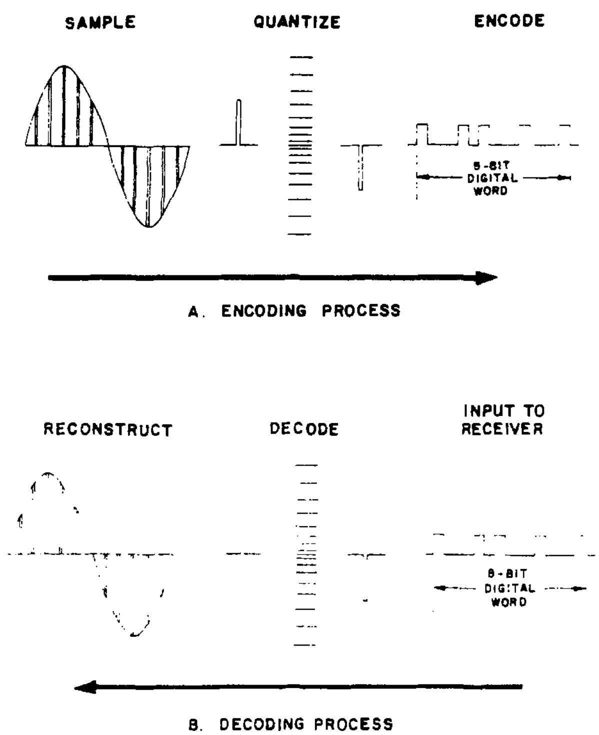

Figure 1

PCM Operations

APPLICATION OF PCM TO CATV

While substantial bandwidth is available in most CATV systems, it is seldom fully utilized. Expanding plant usage by leasing channel space or sharing facilities where PCM is transmitted along with video and other services could provide increased revenue for the cable operator. Potentially, PCM could be employed in the following situations:

a. Leased Channels for Data Transmission for Industrial Users

Although initially designed for voice transmission, PCM systems are particularly well suited for carrying data due to their digital format. The fact that digital transmission systems can carry data at a lower cost, and with much better performance than analog systems, has long been recognized by the communications industry. Transmission of low-speed data (2.4, 4.8 and 9.6 Kb/s) can be accomplished by using existing data modems with tonal outputs and applying them directly into a voice channel of T1 equipment. The data modem output is sampled by the PCM terminal equipment the same as with a voice signal.

Special data modems, which provide a T1 line signal format directly, allow data speeds from 50 to 500 Kb/s. If it is desirable to mix voice and data on the same system, special data modems are available as listed in Table I.[2]

Table I

Available Modems and Channel Arrangements

Wideband Data Modem	Channel Arrangements
GTE Lenkurt 9003A Western Electric T1WB-1	8 Channel - 50 Kb/s
	4 Channel - 50 Kb/s 1 Channel - 250 Kb/s
	2 Channel - 250 Kb/s
GTE Lenkurt 9003A Western Electric T1WB-2	2 Channel - 250 Kb/s
Western Electric T1WB-3	1 Channel - 50 Kb/s 21 Channel - Voice
	2 Channel - 50 Kb/s 18 Channel - Voice
	4 Channel - 50 Kb/s 12 Channel - Voice

New equipment designs provide wideband data modems which promise still more efficient use of the T1, 1.544 Mb/s digital line format.

The wideband channels available on CATV systems are ideal for transmitting high-speed data up to 500 Kb/s, using the standard PCM, T1 line signal format. Leasing of high-speed data channels to industrial users would appear to be a viable market for the CATV industry.

b. Digitally Encoded Video

For applications where security of transmission is important, especially when channels are leased for private signal carriage, digitized video can be useful.[3] Signals, in this format, are relatively immune to repeater - introduced distortion and can be transmitted over long distances with little degradation. These signals, however, require relatively high data rates on the order of 20 to 30 megabits per second for quality picture reproduction. With efficient encoding, such a signal would have a 20 to 30 MHz bandwidth at baseband, thus using the spectrum space of several 6 MHz channels on the CATV system.

c. Voice Communication

In certain geographic areas, particularly outside the United States, it may be attractive to use long-haul CATV trunk systems for transmission of voice communication (primarily T1 telephone signals) along with video programming to interconnect small, relatively isolated areas. A combined system, with its inherent cost savings, could be economically viable, while separate systems could not, perhaps, be justified.

TRANSMISSION TESTS AND RESULTS

a. Lenkurt Tests

For these tests, two, 24-channel PCM signals (1.544 Mb/s each) were combined in a Lenkurt Model 9120A PCM Multiplexer. The output of the 9120A, a 3.156 Mb/s modified duobinary[4] signal,* was fed into a CATV modulator/demodulator pair arranged in a back-to-back configuration.

An oscilloscope, with an eye pattern** (intersymbol interference) display of the signal, and a bit error rate test set were connected to the output of the demodulator. The modulator/demodulator employed amplitude modulation with envelope detection, and vestigial-sideband filtering of the type normally used for video transmission.

The eye pattern of the signal exhibited a high degree of distortion with an unacceptable error rate. The quadrature component, inherent in single-sideband filtering with envelope detection, distorted the signal beyond acceptable limits.

When envelope detection is used, the output is determined by the resultant of the in-phase and quadrature components. In double-sideband transmission, the quadrature component is reduced to zero. However, in single-sideband or vestigial-sideband operation, the presence of the quadrature component

*Modified duobinary is a correlative, level-coded signal which provides spectral shaping into a bandwidth which extends to only one-half the signaling rate.

**An eye pattern is a graphical display used to determine the effects of degradations introduced on digital pulses as they travel over a transmission medium. This pattern is obtained by observing a random pulse train on an oscilloscope, synchronized externally by the clock pulses which drive the random data.

leads to an envelope shape which differs from the modulating signal. One method of reducing the amount of distortion caused by the quadrature component is to reduce the depth (percent) of modulation. This was tried during the laboratory tests. The eye pattern of the resulting detected signal was somewhat improved, but the bit error rate was still unacceptable for back-to-back tests.

When synchronous detection is used, only the in-phase component of the signal contributes to the recovered baseband; thus, requiring that synchronous detection be used for this application to avoid quadrature distortion. It was also concluded that the AGC in the demodulator must be disabled for optimum performance.

b. Sylvania Tests

Transmission tests of PCM were conducted during May 1975 on the Sylvania CATV test system in El Paso, Texas. The majority of the tests employed FM transmission; some minor testing was also conducted using AM.

The PCM signal was a 48-channel, multiplexed T1 telephone waveform (3.156 megabit). Investigations were made into carrier-to-noise ratio requirements, channel interaction, and a brief check on the impact of system group delay on PCM error rate.

For these tests, two T1 signals were combined in a Lenkurt Model 9120A multiplexer whose output signal is compatible with modulators used for radio transmission. The spectrum of the 3.156 Mb/s signal extended to approximately 1.5 MHz (Figure 2). This was well within the bandwidth requirements of modulation/demodulation equipment manufactured for CATV applications.

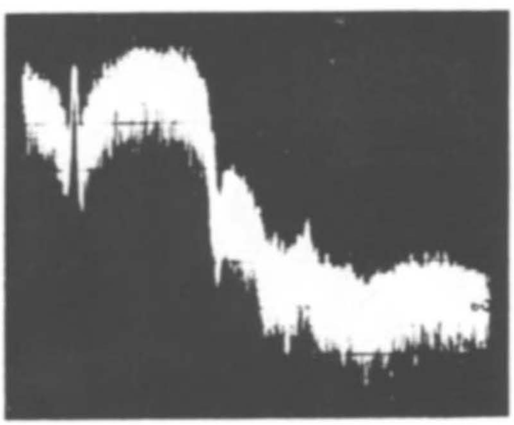

Figure 2

3.156 Mb/s Baseband Output Spectrum From Multiplexer
(+40dBmV full scale; 10dB/cm vertical;
50 KHz/cm horizontal)
Marker at Left Side of Screen
Shows Zero Frequency

The CATV test system, shown in Figure 3, consisted of 20 trunk amplifier stations in cascade, with a 50 to 300 MHz bandwidth, spaced 23dB at 300 MHz. All stations were controlled by two, CW pilot signals which provided for the automatic compensation of gain and slope to adjust for changes in cable attenuation with temperature. The first 10 spans of the cascade were straight 23dB cable sections; the remaining ones had directional couplers (either 3 or 7dB) cut into the line to simulate splits in the trunk, with the cable length adjusted accordingly. The system frequency response (peak-to-valley) was 1.6dB over the 50 to 300 MHz band. This arrangement was the equivalent of over 10 miles of point-to-point system length and provided a convenient facility for tests of this nature.

Figure 3

Sylvania CATV Test System

The equipment setup used for these tests is shown in Figure 4. A Bowmar Model 271A Error Rate Test generated the two 1.544 Mb/s, T1 signals for the input to the transmit side of the multiplexer. One of the recovered, 24-channel, T1 lines from the receiver side of the 9120A was then fed into the test set's receiver input to give a direct readout of error rate on that T1 line. While in normal system application, two multiplexers would be used, one at each end of the system, it was possible to "loop back" the multiplexer output to its own input since the CATV test facility was contained within a relatively small area. With this setup, 48-channel T1 signals could be transmitted concurrently with video for the system tests.

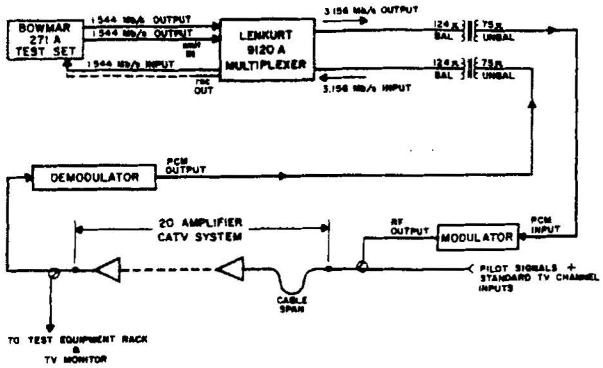

Figure 4

Test Equipment Arrangement for PCM Transmission Tests

FM Tests

The FM modulator/demodulator combination was a Model VFMS-2000 manufactured by the CATEL division of United Scientific Corporation, and operated at a center frequency of 75 MHz.

The modulator had to be run at 90% deviation (approximately 1.5 MHz) in order to obtain sufficient output from the demodulator to drive the multiplexer. The deviation rate was maintained at this level for all subsequent tests. Figure 5 shows the modulator output spectrum at 75 MHz using the 3.156 Mb/s modulation at this deviation.

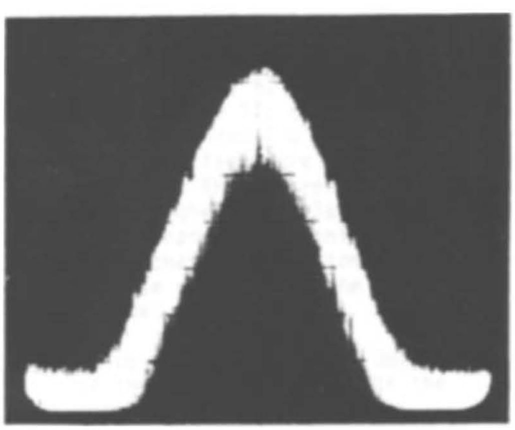

Figure 5

Modulator Output Spectrum at 90% Deviation
3.156 Mb/s Modulation; 75 MHz Center Frequency
(+34dBmV full scale; 10dB/cm vertical;
2 MHz/cm horizontal)

The demodulator output spectrum is shown in Figure 6. This compares well with the input spectrum from the multiplexer (Figure 2), except for the addition of system noise. A qualitative check on the sensitivity of the demodulator to input level variations showed that there was no significant impact on error rate as long as the input level to the demodulator was maintained within the limits shown on the manufacturer's specification sheet (+9.5 to +40dBmV). If the input level went below the specified minimum, the error rate went beyond one in 10^6 immediately because of a reduction in the baseband signal level which could not be tolerated by the multiplexer. Because of this, the input level to the demodulator was set at +20dBmV for all tests.

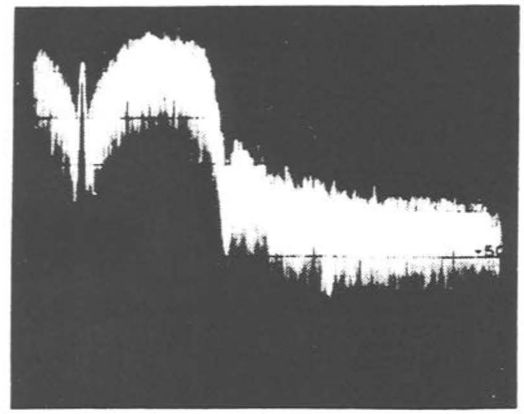

Figure 6

3.156 Mb/s Baseband Output Spectrum from Demodulator
(+40dBmV full scale; 10dB/cm vertical;
500 KHz/cm horizontal)
Marker at Left Side of Screen
Shows Zero Frequency

With the PCM link operating over the CATV system at video level (+30dBmV at 75 MHz) in the absence of any other signals, a plot was made of error rate vs signal-to-noise ratio at the 75 MHz carrier frequency. Carrier level was measured at zero deviation on the modulator. Excess noise was introduced into the system by adding attenuation to the input of the amplifier cascade. This technique reduced the pilot level and the signal level by the same amount; this, in turn, increased the station gain in order to hold the output level constant. With the increased gain, noise was added to the system output without sacrificing signal level into the demodulator. Noise levels were measured on a Hewlett-Packard spectrum analyzer having a 100 KHz bandwidth, and extrapolated to a 4 MHz bandwidth* using their published correction factors.[5]

The curve produced (Figure 7) shows that, if an RF carrier-to-noise ratio of at least 25dB is maintained at the output of the CATV system over the operating temperature range, error rates better than one in 10^8 can be expected.

*All carrier-to-noise measurements in this paper are based on a 4 MHz bandwidth unless otherwise noted.

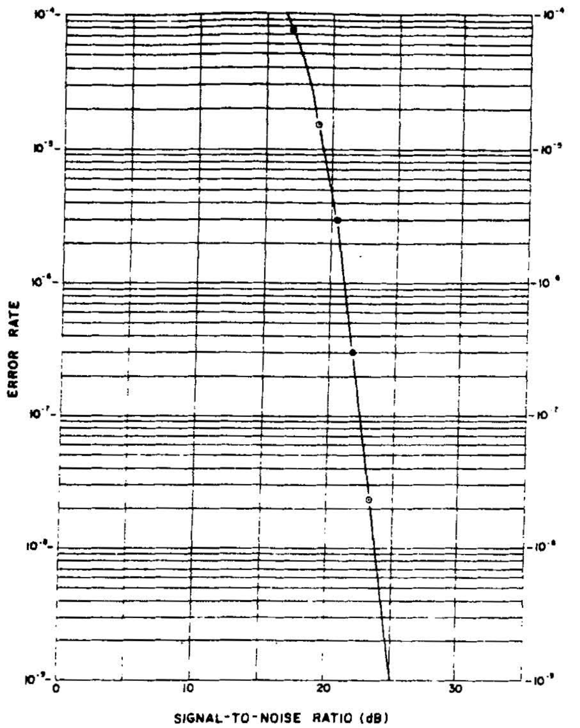

Figure 7

Error Rate vs Signal-to-Noise Ratio
for FM Transmission

The effects of video channels operating simultaneously with the T1 were observed in the next test. The PCM was operated at the same level as the adjacent channel TV signals. Live, off-the-air video was run on channels 2, 6, and 11; channels 4 and 5 were reserved for the T1; channels 3, and 7 through W (except for the channel J pilot and channel A which were inoperative) were run using 100 percent synchronous, 15.75 KHz square-wave modulation. Levels for the higher channels were set in accordance with the standard Sylvania block tilt.* This represented 31-channel operation in addition to the T1. Under these conditions, the following observations were made:

(a) There was no observable degradation on any of the video channels with the T1 operating. .

(b) The composite beat at the CATV system output, measured on Channel 10, was -63dB with the T1 signal "on" or "off".

(c) Visual triple beat margin on the live video was the same with or without the T1.

(d) The error rate on the T1 signal was 2.88 x 10^{-9} , which was not as good as expected since the composite carrier-to-noise ratio on the PCM channel was 46.3dB. This was traced to the demodulator's sensitivity to Channel 6. In fact, with the PCM off, the video output of the demodulator showed detection of Channel 6 sync pulses.

Considering that, in the future, 96-channel multiplexing equipment with increased bandwidth may be available, it would be preferrable to run the PCM at levels lower than the video to minimize its contribution to composite beat build-up in the CATV system. It was desirable, therefore, to run the PCM channel 10dB below the level of the adjacent channel video. Since demodulator sensitivity to the adjacent channel precluded doing this, all remaining tests were performed with Channel 6 disabled.

A long-term error rate test with the PCM operating 10dB down from video (+20dBmV) produced an error rate of 2.3x10^{-11}. This was a 15-hour, 35 minute run with the PCM operaging simultaneously with 30 modulated TV channels. Composite carrier-to-noise ratio on the PCM channel was 36.3dB.

Finally, the PCM was transmitted over the system after sub-VHF diplex filters were added to each trunk station. These filters are used to establish bi-directional system operation and added about 40 nanoseconds of differential group delay at the 75 MHz carrier frequency; this differential delay is specified over the 3.58 MHz video-chroma carrier separation normally used for television transmission. With the added delay produced by these filters, a two-hour test yielded an error rate of 3.598 x 10^{-10}, using the same operating conditions as in the 30-channel test described previously.

AM Tests

A few tests were also run with a AM video modulator/demodulator pair designed for normal television transmission operated on Channel 2. Figure 8 shows the modulator output spectrum, where some slight clipping of the lower sideband by the vestigial filter is noticeable.

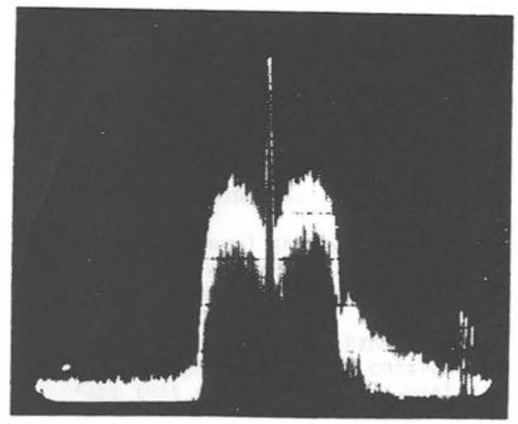

Figure 8

AM Modulator Output Spectrum
3.156 Mb/s Input; 55.25 MHz Carrier Frequency
(+34dBmV full scale; 10dB/cm vertical;
1 MHz/cm horizontal)

*Channels 2-E at +30dBmV; F-13 at +32dBmV; J-W at +34dBmV.

In order to get satisfactory PCM transmission, certain operating conditions had to be maintained on the modulator and demodulator;

(a) The percentage of modulation had to be reduced to 50 percent, presumably, to minimize the effects of quadrature distortion in the video detector from the clipping of the lower sideband.

(b) The IF and AGC levels in the demodulator had to be very carefully set to obtain the proper detected output level. The AGC system in this particular equipment used sync-tip reference. Since the PCM is transmitted without sync pulses, some limited AGC action will be obtained by detection of the composite signal making the setup of the AGC very critical.

There were also slow, long-term, level shifts due to AGC drift which precluded making any extensive measurements. However, the following could be determined:

(a) With the T1 signal operating at video level along with 33 modulated TV channels and 140 nanoseconds differential group delay, an error rate of 5.39×10^{-9} was obtained for a 25-minute test. This was with a 48dB carrier-to-noise ratio.

(b) When the carrier-to-noise ratio was reduced to 35dB, the error rate degraded to beyond one in 10^{4} ; at a 40dB carrier-to-noise ratio, a 5.8×10^{-7} error rate was recorded.

These AM tests, although brief, indicated problems similar to those pointed out by the GTE Lenkurt work, and since this was the only AM equipment available, no further testing was conducted.

EQUIPMENT REQUIREMENTS

These experimental tests point to certain performance requirements for the modulation/demodulation equipment and CATV transmission system if PCM and video signals are to be transmitted simultaneously without degradation.

a. Modulation/Demodulation

Tests conducted thus far indicate that coaxial cable and cable amplifiers do not constitute a major impairment to the transmission of high-speed PCM signals over CATV systems. The CATV modulator/demodulator are the most critical points in the system. Such equipment should be specified as follows:

(1) The modulator should be designed for color TV transmission. This should include pre-equalization circuits to correct for phase distortion inherent in the shaping circuits of the modulator, and optimized circuits to provide the minimum linear differential phase characteristics (equivalent to minimum differential delay) necessary for high quality color TV signals.

(2) Synchronous detection should be employed in the AM demodulator in order to achieve high performance levels with respect to differential delay and gain and quadrature distortion. The keyed AGC circuit in the demodulator must also be disabled.

b. CATV Transmission System

In general, if the CATV transmission system has been designed for video-quality transmissions, no problems will be encountered in transmitting PCM with an acceptable error rate. The curve of Figure 7 shows that signal-to-noise ratios of 30dB or more on the PCM channel will give excellent digital signal recovery. Discrete and composite beat distortion products should be maintained at comparable levels to avoid unsatisfactory error rates. These reduced signal-to-noise ratio requirements allow the PCM signals to be run on the system at levels 10 to 15dB below the video, thus minimizing contributions of the PCM channel(s) to distortion products affecting the video signals.[6] Systems designed exclusively for PCM transmission can take advantage of the lower carrier-to-distortion ratio requirements to increase amplifier spacing and reduce the size of the cascade.

SUMMARY

Overall, the experimental tests show, especially for the FM transmission system, that 3.156 Mb/s PCM can be transmitted over CATV systems without degradation to either the PCM or the video. Certain guidelines, however, should be followed:

(1) Sensitivity of the PCM demodulator to adjacent channel signals must be considered. If it is unacceptably high, extra preselection must be specified, or, preferably, a guard band maintained between the PCM channel(s) and the video.

(2) Sufficient signal level and carrier-to-noise ratio must be maintained at the input to the demodulator as the system levels vary with temperature. A 30dB carrier-to-noise ratio would provide a good basis for system design and guarantee sufficient signal-to-noise at baseband for proper operation of the PCM decoding equipment.

(3) The PCM channel should be run 10dB below video to minimize its contribution to composite beat build-up in the CATV system.

(4) Selection of the PCM channel carrier frequency should take into consideration the fact that composite triple-beat distortion is worst at the standard TV channel video carrier frequencies. If PCM is operated "off channel", triple beat distortion will have a lesser effect on the PCM error rate.

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