PERFORMANCE OF DIGITAL TRANSMISSION TECHNIQUES FOR CABLE TELEVISION SYSTEMS

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Abstract

An evaluation of complex modulation techniques for the transmission of digital information for advanced television applications is currently underway at CableLabs. The performance of various digital modulation techniques in the cable television transmission medium co-existent with standard NTSC analog video channels has been investigated. Both laboratory and field evaluations on existing cable systems are presented.

Introduction

The performance measure customarily utilized in characterizing digital modulation is the bit error rate. The bit error rate (BER) is dependent upon the carrier to noise ratio, or more precisely the bit energy to noise spectral density ratio. Either of these metrics provide the probability of error in terms of the distance between signals in energy space divided by the noise power for the additive white Gaussian noise environment.

The optimum receiver receives a waveform which is comprised of a transmitted signal corrupted by adding white Gaussian noise. The signal can be replaced by an equivalent vector form, and the noise process by a relevant noise process that can also be represented in vector form. This is done by defining a set of orthonormal time waveforms which can be used in linear combinations to represent both the signal and noise vector components (e.g., two quadature modulated carrier phases).

The vector components are derived at the receiver through a correlator or matched filter to the orthonormal time waveforms. The decision as to which signal was sent is made by comparing the distance of the received vector to all possible signal vectors. The receiver decides that a particular signal was sent if the received signal vector is closest to it. An error occurs if the received vector is closer to a signal vector that is different from the originally transmitted one.

For PAM modulated signals with non binary symbols, a rectangular constellation and decision regions result. The constellation diagram represents the signal vectors in a two dimensional space. The rectangular nature of the signals and their resulting decision boundaries are shown for 16 QAM and 4 VSB in Figures 1 and 2 respectively.

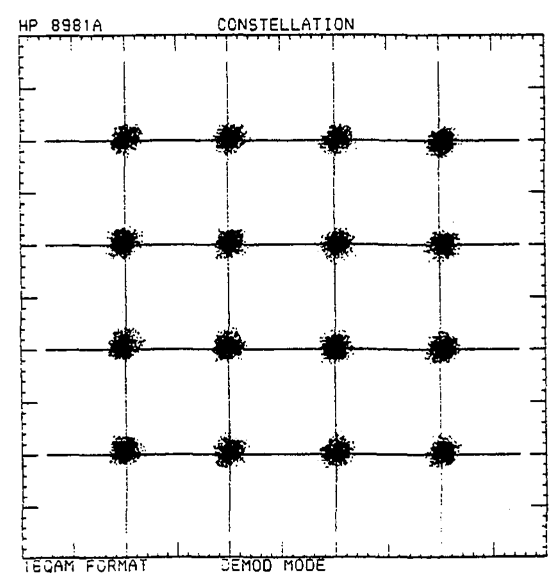

Figure 1 - 16 QAM Constellation

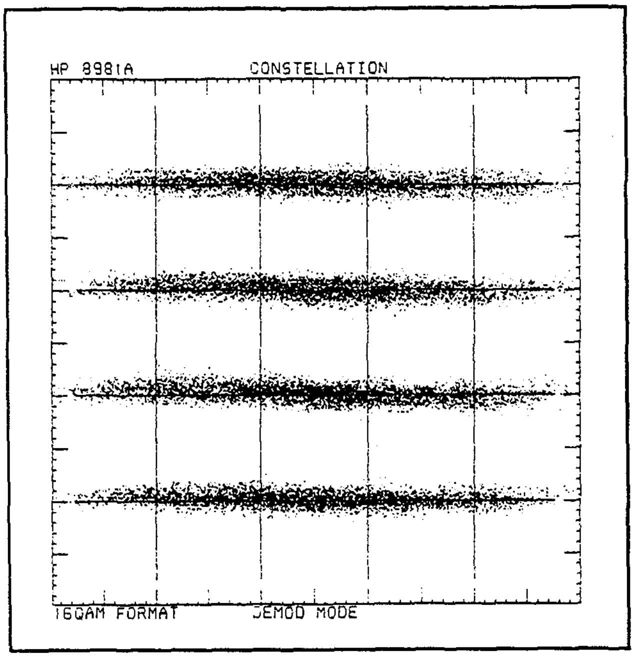

Figure 2 - 4 VSB Constellation

This Euclidean distance concept in signal energy in the presence of such noise can be reduced in the presence of additional impairments such as channel nonlinearities, intermodulation, and intersymbol interference due to channel bandwidth restrictions or reflections from impedance mismatches. These impairments reduce the "effective" carrier to noise ratio of an equivalent noisy but unimpaired channel. The bit error rate is calculated as the probability of the equivalent noisy signal erroneously crossing a decision boundary associated with the transmitted symbol (or group of bits) into another region associatedwith a different symbol. The effective carrier to noise with reduced implementation noise margins degraded by channel impairments has been studied to estimate the expected bit error rate of modern terminal equipment with practical performance limitations.

Transmission Testing Method

Two modulation formats were studied. The first format is 16 QAM double sideband pulse amplitude modulation format with quadrature carrier multiplexing and 4 levels (representing 2 bits) per carrier phase with the carrier placed symmetrically in the center of the band. The second format is 4 VSB, which is a (nearly) single sideband pulse amplitude modulation format with a small (5 percent) vestige about the carrier at the band edge. The modulated average signal power was set approximately 10 dB below NTSC carrier level.

The approach suggested for the performance evaluation of digital modulation on the cable distribution plant is vector modulation or constellation analysis. The digital data carrier is discretely modulated in phase and amplitude to convey groups of binary digits (words) as vectors in carrier phase space. The instantaneous switching between carrier phase states requires infinite channel bandwidth. Restrictions on the modulating data signal bandwidth result in intersymbol interference in practical systems.

Evaluation of ISI is possible by examination of the baseband data modulating channel response given by an eye pattern or diagram, where overlapping data symbol periods are superimposed to determine the reduction of noise margin due to ISI. The closure of the eye results in increased bit error rate, since noise in the channel is much more likely to force the signal to cross a decision boundary. The spread in the signal constellation clusters as well as shifts in position due to other channel impairments can be characterized by the constellation diagram. The constellation is a set of sampled points in carrier phase space with the carrier sampling times optimally chosen to coincide with the maximum eye openings in time of the inphase (I) and (for QAM only) the quadrature (Q) channels.

The performance of generalized digital modulation signal sets can be generated and analyzed with vector modulation equipment. Although bit error rate cannot be directly measured, it can be inferred from the constellation and eye pattern parameter measurements. These measurements can be made without constructing modems that require carrier recovery, symbol synchronization, clock recovery, data detection, differential decoding, etc.

Laboratory Tests

Vector modulation equipment available from Hewlett Packard along with prototype digital Nyquist pulse shaping filters and frequency conversion equipment was employed for the digital transmission evaluations. A pseudorandom bit sequence (PRBS) generator provided the data for the digital carrier modulation. The random data modulates I and Q IF carriers in both formats. Channel filters must be designed and inserted to shape the modulation spectrum and limit the modulated carrier bandwidth. A 6 MHz channel is utilized within the 41 to 47 MHz range with an appropriate Nyquist response rolloff characteristic.

A source bit rate of 18 Mbps from the PRBS generator divided between I and Q carrier phases (for 16 QAM) or carried in the I phase only (for 4 VSB) with 10 percent rolloff (excess bandwidth) occupied a 6 MHz channel. The coherent reference from the vector generator was normally used (except for phase noise testing) to demodulate the modulated data IF carrier at the vector modulation analyzer. Constellation and eye pattern measurements were made without the need for carrier recovery.

The modulated IF signal was supplied to a Scientific Atlanta RF modulator IF input with a crystal oscillator selected for the television channel desired for data transmission. A complementary RF demodulator recovers the modulated data carrier at IF, after being degraded by added impairments.

The recovered I and Q data bitstreams can be examined for mean square eye closure, phase offsets, and dispersion in the recovered constellation samples from the vector modulation analyzer. Several hundred thousand points were downloaded via a GPIB interface to a computer for further analysis and estimation of effective carrier to noise ratio and expected error rate.

Some mean square eye closure results from the lab tests done on the CableLabs test bed in the Advanced Television Test Center in Alexandria, VA are given in Table 1 for various cable

LAB DATA - FROM CableLabs TEST BED			
TTS	DESCRIPTION	QAM %	VSB %
1	Unimpaired	13.0	14.5
2	Echo @ 300ns -15.7dBc	35.0	33.4
2A	Echo @ 300ns -20.7dBc	21.5	20.5
2B	Echo @ 300ns - 25.7dBc	15.3	15.6
3	CW Ingress at -23dBc	30	32
4	CTB at -32.5dBc (cw carriers)	16.6	18.8
5	Phase Noise -91.6dBc (1Hz) at + 20kHz from carrier	23.5	25.0
6	Composite Second Order at -32dBc (cw carriers)	15.0	16.5
7	Hum Mod, 120Hz, 4.6%	16.5	17.5

Table 1 - Lab results from the CableLabs test bed in Alexandria, VA.

impairments. The "unimpaired" eye closure of 14% is due to implementation loss, analog filtering, and the modulation and frequency translation equipment. Data for a short duration reflection characteristic of cable systems is shown for -15, -20, and -25 dB. The composite triple beat level for comparable eye closure is higher than would be present for satisfactory NTSC reception. The same situation applies for composite second order interference. Phase jitter from oscillator phase noise and power supply induced residual FM show a significant degredation at levels that would be unnoticeable on NTSC.

Field Tests

The laboratory tests may be repeated in the field on the TCI cable system in Boulder, CO. An additional complication arises due to the need

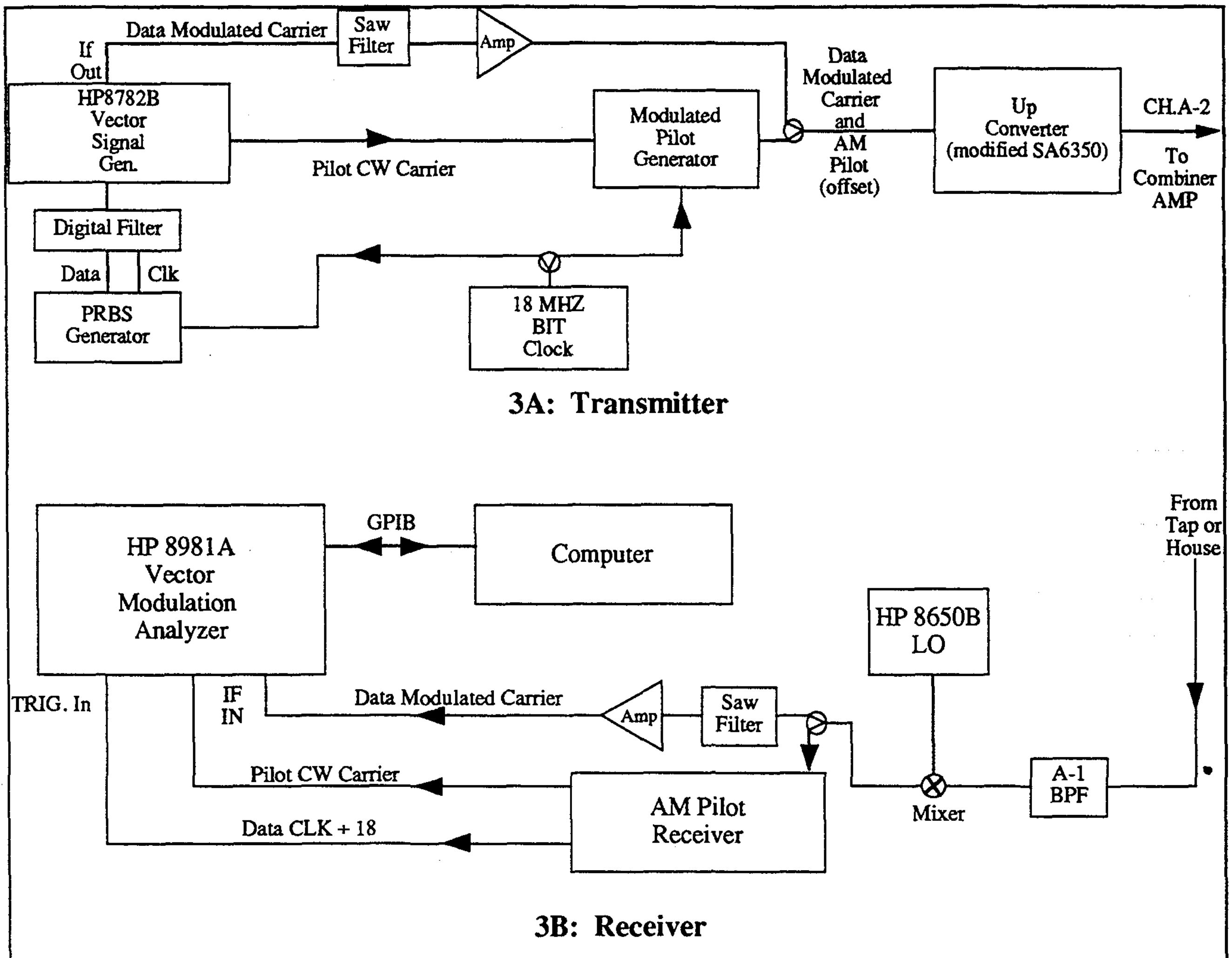

Figure 3 - Digital Transmission Test Block Diagram

for a recovered carrier reference and symbol timing for vector demodulation and sampling of the I and Q modulated carrier phases. This unmodulated carrier reference should be phase locked precisely to the data modulated carrier IF frequency.

During the field tests, both 4 VSB and 16 QAM signals were generated to study the effect of cable impairments. The complete test setup for the field (and the lab without the carrier and symbol timing reference recovery portions) is shown in Figure 3. The generation of the I and Q baseband data streams were done in the headend in the same way as in the test bed facility using a pseudo-random binary sequence generator (PRBS) and a digital filter. The digital filter generated the necessary Nyquist shaped, bandlimited data signals which drove the external inputs of an HP8782B Vector Signal Generator. The HP Vector Signal Generator generated both a coherent pilot CW carrier at the output frequency, and a data modulated carrier with the I and Q data.

At the receive site (which was kilometers away in the field test, but less than one meter in the lab test), a coherent pilot CW carrier reference was needed by the HP8981A Vector Modulation Analyzer to demodulate its received data carrier into baseband I and Q data streams. Additionally, the Vector Modulation Analyzer needed an external input data clock to accurately determine symbol timing. This presented a design problem to the recovery of the data over the cable TV plant because the coherent pilot reference occupies the same spectral space as the data modulated carrier.

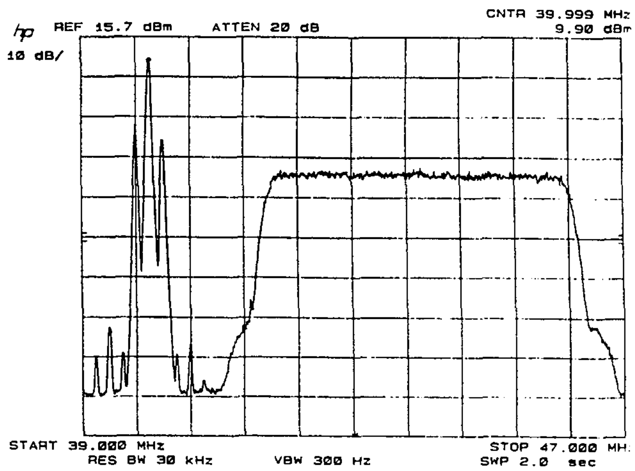

Figure 4 - Spectrum of Modulated Data Carrier and AM Pilot Tone

The solution implemented was not to build a modem, but to use an offset AM carrier pilot to achieve both carrier and data timing references. The AM pilot carrier was offset out of band from the modulated data carrier, and a 200 kHz AM modulation tone was put on the offset pilot. The AM pilot carrier was now 1 MHz below the 41-47 MHz IF band used by the modulated data carrier. Figure 4 shows the spectrum of the data modulated carrier and the offset AM modulated pilot tone.

The 200 kHz tone was used in the AM Pilot Receiver to both regenerate the carrier offset, and provide a data clock to trigger the external trigger on the vector analyzer.

At RF the spectrum is inverted from IF. The Modulated Pilot Generator at the headend used the 18 MHz Bit Clock and the pilot CW carrier to generate the offset AM pilot, and it was summed with the data modulated carrier for an input to an upconverter. A Scientific Atlanta 6350 modulator with a frequency agile output converter (FAOC) was used for upconversion of the pilot plus modulated carrier. Normally, the phase noise of the agile upconverter would have been troublesome, but the offset carrier recovery scheme provided immunity to phase noise, as both the out of band AM pilot and modulated carrier undergo identical phase jitter in the conversion process.

It can be shown that any frequency offset in the RF local oscillator will be present in both the modulated IF data carrier and the recovered carrier reference. Hence carrier recovery without phase error is achieved at the remote measurement site, and all the measurements previously described for the laboratory testing may be done in the field.

At the receive site, the signal was amplified and put through a bandpass filter (BPF). Channel A-1 was used in the TCI Boulder, CO system. An HP8656B Signal Generator was used as a downconverter local oscillator (LO), and a double balanced mixer brought the data modulated carrier and the offset AM pilot to the IF frequency band. At IF, the signals were split and the data modulated carrier was bandpassed through a saw filter and presented to the input of the demodulator in the HP8981A Vector Modulation Analyzer. Off of the other split, the AM modulated carrier was put into the AM Pilot Receiver. The AM pilot receiver performed two tasks. The first was to recover an unmodulated carrier reference for demodulation, and the second was to provide a data clock that the Vector Modulation Analyzer could use for triggering, which provided the correct sampling times for the symbols.

The Transmitter and Receiver carrier and data clock reference circuitry was used for both

16 QAM and 4 VSB. With both transmission methods, the AM modulated pilot carrier remained at an IF frequency of 40 MHz. With 4 VSB, the regenerated carrier at 42 MHz was offset by 2 MHz from the 40 MHz AM carrier. In the 16 QAM case, the regenerated carrier at 44 MHz was offset by 4 MHz from the 40 MHz AM carrier. The same 41 to 47 MHz IF band was used for both VSB and QAM modulated data carriers.

Some mean square eye closure results from the field tests done on the TCI system in Boulder, CO are given in Table 2 for various tap and subscriber home locations. The signal received both at the tap and inside the house at the TV receiver input were measured. The mean square eye closure for several locations including a fiber hub are shown. The large variability on the resulting impairment between location in the system and between the tap and the premises wiring in this small sample is significant. The variability of performance for digital modulation within the cable plant at the subscriber drop merit additional investigation.

FIELD DATA		
FIELD LOCATION	QAM EYE CLOSURE %	VSB EYE CLOSURE %
TCI Headend	13.2	14
CableLabs Lab	14.2	15.7
House 1 Tap 1	32 16	34 17.9
House 2 Tap 2	16 14.7	(Note 1) 16.2
House 3 Tap 3	14.7 14.4	15.9 17.1
House 4 Tap 4	19.9 17.2	23.3 19
House 5 Tap 5	22.1 20.9	22.5 24.4
House 6 Tap 6	16 14.8	15.5 15.2
Field Fiber HUB	19.9	21.6
Lab Fiber + 12AMPS	16.1	16.2

Note 1: Equipment out of service

Table 2 - Field Results from the TCI System in Boulder, CO.

Conclusion

It can be noted that rather small reflections causing intersymbol interference results in significant eye closure. This source of interference is most readily caused by cable reflections due to mismatches inside the house. This suggests that adaptive equalization may be required in many receive locations for a uniform level of reliable reception (suitably low error rate) at the lower signal levels that are nominally suggested (and used in this evaluation) for digital cable transmission.

The results obtained in both laboratory and field trials can be used to infer required modem performance in terms of the relative level of importance of the residual impairments at the receiver. A test of actual bit error rate requires the modem, as the carrier recovery, data, clock recovery, and symbol timing and synchronization information (and resulting equipment implementation losses) are needed to recover and evaluate the continuous baseband data stream at the destination. However it is possible to estimate the error rate obtained using the raw data acquired in the present study. This is the subject of a future companion paper.