HIGH DEFINITION TELEVISION - DEFINING THE STANDARD

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Abstract

In February, 1993 the Federal Communications Commission's Advisory Committee on Advanced Television Service recommended that the four digital ATV transmission systems have proposed improvements made and be re-tested to determine the best system for North America. The proponents were also encouraged to form an alliance to combine the best parts of the individual systems into one superior system. The four proponents subsequently formed the "Grand Alliance" to develop a single advanced television system that would incorporate the best parts of the various proposed systems. By late fall of 1993 all aspects of the system had been determined except which transmission system to use. The Alliance proposed that the Advisory Committee participate in the testing of the proposed transmission systems to minimize the time required to review the results and agree on the recommended standard.

The tests started in early January, 1994 and were completed in early February. The results of the tests showed the vestigial sideband implementation proposed by Zenith to be better, in most respects, than the QAM implementation proposed by General Instrument. The VSB system was recommended as the ATV standard with the QAM system retained as the backup. This paper reviews the results of the cable portion of the tests.

BACKGROUND

The Advisory Committee on Advanced Television Service was appointed by the Federal Communications Commission in 1987 oversee the development and testing of potential advanced television systems. Of the initial twenty plus proposals only four digital transmission system proposals made it through the first round of tests and were recommended for a second round of tests. The proponents were given time to incorporate proposed improvements with final tests originally scheduled to begin in the spring of 1993. At the same time the proponents were encouraged to try to come together with a single proposed system which would incorporate the best portions of the various systems and result in the best possible system.

The proponents announced the formation of the "Grand Alliance" on May 24, 1993, after the first system had arrived at the Advanced Television Test Center for re-testing but prior to the beginning of the tests. The Grand Alliance, consisting of: AT&T, the David Sarnoff Research Center, General Instrument, Massachusetts Institute of Technology, North American Philips, Thomson Consumer Electronics and Zenith Electronics, indicated that the system to be proposed would consist of the best parts of all the individual systems, selected to provide the best possible system.

The Advisory Committee accepted the proposal from the Alliance and gave it the time necessary to develop the final system. The Technical Subgroup of the Special Panel of the Advisory Committee was charged with overseeing the development of the final system. By the end of November, 1993 all but the transmission system had been specified. The Alliance had narrowed its proposals down to two modulation systems, the QAM system, originally proposed by GI/MIT, and the VSB system proposed by Zenith. Each of these systems had a basic, single ATV channel data rate and a second, high data rate option for cable which would carry data for two advanced television channels within one 6 MHz channel.

The Alliance initially planned to perform system selection tests privately and to have the results reviewed by the Advisory Committee. Later, the Alliance decided that it would speed the process to have the Advisory Committee participate in the testing. The tests were scheduled to begin at the Advanced Television Test Center in Alexandria, VA in January 1994. The equipment arrived in early January with a couple of changes to the approved transmission systems. Zenith withdrew their 4 and 6-VSB systems and replaced them with a single 8-VSB system which had a superior trellis coding implementation. The data capacity of the GI 256-QAM system was increased from 32.9 Mbps to 38.2 Mbps.

The tests began in early January, 1994 and were completed in just over a month. The cable portion of the tests were performed by CableLabs during the week of January 24th. The systems tested were the 32-QAM standard data rate and 256-QAM high data rate systems proposed by GI and the 8-VSB standard data rate and 16-VSB high data rate systems proposed by Zenith. Only the cable portion of the tests were performed on the high data rate systems since they are not intended for over-the-air use.

TEST PROCEDURE

Only transmission modems were to be tested, not complete HDTV systems, which made it impossible to observe interference levels by looking at the picture. This problem was overcome by estimating the bit error ratio (BER) which would result in errors first becoming visible in the picture. That error ratio, 3 x 10-6, was then defined as the threshold of visibility (TOV). The impairment level for TOV was the highest level of impairment which would result in a BER equal to or better than 3×10^{-6}. This was determined by increasing the level of the impairment until the BER was worse than 3×10^{-6} then reducing the impairment in small increments until the BER was at or just better than 3 x 10-6. The BER was obtained by observing errors for 20 seconds and calculating the BER. The BER had to remain below the threshold value for three consecutive 20 second periods to be classified as the threshold.

Four of the tests were repeated as multiple impairment tests in which the main impairment, CTB, CSO, phase noise or residual FM, was reduced in level below threshold and Gaussian noise was added to the signal until a new threshold was found. This test showed the ability of the system to operate in the presence of multiple impairments and gave an indication of the trade-off that took place between Gaussian noise and the main impairment under test.

TEST RESULTS

Signal-to-Noise (S/N)

Signal-to-Noise is the basic test to determine the threshold level of digital systems operating in the presence of thermal (Gaussian) noise. It is a repeatable test and it is one of the main constraints in designing cable television systems. In the digital ATV systems the signal power is specified as the average power of the signal within the 6 MHz band and the Gaussian noise is measured in the same 6 MHz band. This is slightly different from the NTSC measurement practice where the noise bandwidth is only 4 MHz.

The low data rate systems (32-QAM and 8-VSB) produced equal threshold S/N values of 14.8 dB. The high data rate systems showed some differences with the 256-QAM having a threshold value of 29.3 dB while the 16-VSB had a somewhat better threshold value of 27.6 dB.

Composite Triple Beat (CTB)

A second major area of interest for cable operators is composite triple beat, a distortion created each time the cable signals are amplified. The CTB product generated by the NTSC visual carriers on a cable system falls 1.25 MHz above the lower band edge, i.e. at what would normally be the location of the NTSC visual carrier. Each of the digital modulation systems reacted differently to CTB products falling at this location.

The 8-VSB system, with a threshold of 12.6 dB, performed much better than the 32-QAM system, which had a threshold of 32.0 dB. The superior performance of the VSB system was due, in part, to the presence of a comb filter which is turned on when the receiver detects co-channel interference or CTB products. CTB products fall at the same frequency as a co-channel visual carrier resulting in the receiver interpreting the CTB interference as a co-channel interference and turning on the comb filter. There is a noise tolerance penalty when the comb filter is turned on, therefore, the filter is used only when co-channel is present at a sufficiently high level.

The 16-VSB modem, with a C/I threshold of 44.0 dB, performed better than the 256-QAM system which had a C/I of 46.5 dB. The comb filter is not present in the 16-VSB modem as it is intended for cable system use only and should not need co-channel protection.

A multiple-impairment test was performed to determine the trade-off between CTB and Gaussian noise. It was expected that as the amount of CTB was reduced the receiver tolerance to

Gaussian noise would increase. The CTB interference level was reduced by 1, 2, 3, 6, 9, and then 12 dB below the threshold level and Gaussian noise was adjusted until the receiver threshold was again reached and the S/N ratio at this threshold was measured. See Table 1.

The results for the 32-QAM, 256-QAM and 16-VSB modems were as expected with the noise tolerance increasing as the CTB interference was reduced. The 8-VSB system acted opposite to the expected manner and became less tolerant of noise as the CTB level was reduced. This was attributed to the comb filter having trouble deciding whether to switch in or out due to the large changes in the level of the CTB interference as contributing carriers came in and out of phase. In production receivers there may be a switch to turn off the comb filter and the selection algorithm may be better optimized.

Table 1
CTB vs. Gaussian Noise

	32 QAM	8 VSB	256 QAM	16 VSB
CTB TOV C/I	32.0 dB	12.6 dB	46.5 dB	44.0 dB
S/N @ CTB TOV-1 dB	—	—	32.9 dB	28.0 dB
S/N @ CTB TOV-2 dB	—	—	31.7 dB	27.9 dB
S/N @ CTB TOV-3 dB	16.8 dB	19.3 dB	30.7 dB	27.8 dB
S/N @ CTB TOV-6 dB	15.5 dB	19.0 dB	29.6 dB	27.7 dB
S/N @ CTB TOV-9 dB	15.2 dB	22.8 dB	29.4 dB	27.7 dB
S/N @ CTB TOV-12 dB	15.2 dB	25.9 dB	29.4 dB	—
S/N with no CTB	14.8 dB	14.8 dB	29.3 dB	27.6 dB

Composite Second Order (CSO)

Push-pull amplifiers were introduced to reduce the level of second order beats when cable systems expanded beyond 12 channels but the introduction of AM fibre links has returned second order distortion to an interference which must be considered in system design. The second order distortion products fall 1.25 MHz above the NTSC visual carrier or 2.5 MHz above the lower band edge.

The 32-QAM modem performed very well in the presence of CSO interference with a C/I of 10.6 dB while the 8-VSB reached threshold at 28.5 dB. Among the high data rate systems, the 16-VSB modem had the better performance with a threshold C/I of 33.4 dB while the 256-QAM high data rate modem threshold was reached at 37.0 dB

The multiple impairment test was conducted by reducing the CSO level and increasing noise until a new threshold was found with both noise and CSO present. All modems behaved as one would expect with noise tolerance increasing as CSO was reduced. The full results are shown in Table 2.

Table 2
CSO vs. Gaussian Noise

	32 QAM	8 VSB	256 QAM	16 VSB
CSO TOV C/I	10.6 dB	28.5 dB	37.0 dB	33.4 dB
S/N @ CSO TOV-1 dB	22.0 dB	15.5 dB	35.8 dB	33.7 dB
S/N @ CSO TOV-2 dB	19.6 dB	15.2 dB	32.8 dB	31.7 dB
S/N @ CSO TOV-3 dB	18.4 dB	15.2 dB	31.8 dB	30.3 dB
S/N @ CSO TOV-6 dB	18.1 dB	14.8 dB	30.4 dB	28.6 dB
S/N @ CSO TOV-9 dB	18.0 dB	14.7 dB	29.7 dB	28.2 dB
S/N @ CSO TOV-12 dB	17.2 dB	14.7 dB	29.6 dB	27.8 dB
S/N with no CSO	14.8 dB	14.8 dB	29.3 dB	27.6 dB

Phase Noise

The presence of phase instability on the local oscillators used in channel conversion will introduce phase noise into the signal. Synthesizers are used in many modulators and heterodyne processors to create the local oscillator signals. NTSC signals are very tolerant of phase noise and can tolerate the use of local oscillators with relaxed specifications for the phase noise. Unfortunately, digital modulation systems are less tolerant of phase noise and it will be a constraint in equipment designs. Phase noise level is measured 20 kHz from the carrier in a 1 Hz bandwidth and referenced to the level of the carrier on which it is measured.

The 8-VSB modem was more tolerant of phase noise than the 32-QAM modem with a C/I of 77.1 dB compared to an 81.3 dB C/I. The 16-VSB modem performed slightly better than the 256-QAM system with a C/I of 83.0 dB compared to an 84.2 dB C/I.

A multiple impairment, phase noise vs. Gaussian noise trade-off test was performed. All systems displayed a normal reaction by increasing their tolerance for Gaussian noise as the phase noise level was reduced. Full results are given in Table 3. The 32-QAM, 8-VSB and 256-QAM systems were within one dB of the random noise threshold when the phase noise was reduced 6 dB below threshold level while the 16-VSB modem was within one dB with only a 1 dB reduction in phase noise.

Table 3
Phase noise vs. Gaussian Noise

	32 QAM	8 VSB	256 QAM	16 VSB
Phase Noise TOV C/I	81.3 dB	77.1 dB	84.2 dB	83.0 dB
S/N @ Ø Noise TOV-1 dB	17.4 dB	22.9 dB	34.5 dB	28.4 dB
S/N @ Ø Noise TOV-2 dB	16.3 dB	21.1 dB	31.8 dB	28.4 dB
S/N @ Ø Noise TOV-3 dB	15.9 dB	19.0 dB	30.6 dB	28.3 dB
S/N @ Ø Noise TOV-6 dB	14.8 dB	15.8 dB	29.7 dB	28.2 dB
S/N @ Ø Noise TOV-9 dB	—	15.1 dB	29.6 dB	28.1 dB
S/N @ Ø Noise TOV-12 dB	—	14.9 dB	29.4 dB	28.1 dB
S/N with no Ø Noise	14.8 dB	14.8 dB	29.3 dB	27.6 dB

Residual FM

A very small amount of ripple on the DC power supply feeding the oscillator can introduce residual FM into local oscillators. While the NTSC signal is very tolerant of residual FM, digital signals are much less tolerant. Tight design specifications for residual FM may be necessary on oscillators designed for use with digital signals.

The threshold levels of residual FM were similar for the two low data rate modems. The 32-QAM system tolerated an 8.4 kHz peak FM signal while the 8-VSB modem performed slightly better with a threshold of 8.8 kHz. The 256-QAM modern was capable of handling an impressive 70 kHz peak residual FM while the 16-VSB modem could only tolerate a 4.7 kHz signal.

The modems were tested to determine the trade-off between random noise and residual FM. The 32-QAM modem tolerance for noise increased as the residual FM was decreased but the 8-VSB tolerance remained constant as the residual FM was decreased. Both of the high data rate modems were within 1 dB of the noise threshold when the residual FM was reduced to 50% of the threshold value.

Table 4
Residual FM vs. Gaussian Noise

	32 QAM	8 VSB	256 QAM	16 VSB
Res. FM TOV	8.4 kHz	8.8 kHz	70 kHz	4.7 kHz
S/N @ 0.75 Res. FM TOV	23.0 dB	21.1 dB	34.2 dB	34.5 dB
S/N @ 0.5 Res. FM TOV	19.1 dB	21.0 dB	30.9 dB	28.5 dB
S/N @ 0.25 Res. FM TOV	16.1 dB	21.0 dB	30.0 dB	28.2 dB
S/N with no Res. FM	14.8 dB	14.8 dB	29.3 dB	27.6 dB

Pull-In Range

During the life of a receiver there can be some drift in the local oscillator frequency which the receiver must be able to overcome to tune a desired channel. In addition, some channels are offset in frequency to improve interference performance or to meet federal regulations. The modems were tested to determine their ability to tune a signal that was offset from nominal frequency allocation. A value of 100 kHz was determined to be a reasonable offset which the modems should be capable of tuning and was selected as the maximum pull-in to be reported.

The 8-VSB, 256-QAM and 16-VSB modems were capable of tuning at least a ±100 kHz offset. The 32-QAM modem could only tune a +74 kHz and -80 kHz offset.

Hum Modulation

As signals move down the cable system they are amplified a number of times. If the DC power supplies are not properly regulated some power line frequency amplitude modulation of the signal can occur. With NTSC signals, this interference becomes visible as bars moving up the picture when the modulation reaches about 3%. In the presence of high hum modulation the digital pictures may exhibit block errors or the picture may freeze.

All of the modems were capable of operating with hum modulation greater than 3%. The 32-QAM continued to operate at 15.2 % modulation, the highest amount available on the test bed. The 8-VSB and 16-VSB were equivalent at 7.7% and 7.6% respectively. The 256-QAM modem reached threshold with the modulation at 5.7%.

Summation Sweep

Cable operators commonly use some form of summation sweep to determine and adjust the frequency response of the systems. High level summation sweep systems were expected to cause problems with the digital signal as data is lost when the sweep signal passes through the channel. The test was performed using a Wavetek sweep set 10 dB above the digital signal and programmed to spend about 0.2 msec in each 6 MHz channel. The amount of interleaving used in the encoder helps determine if the amount of data lost exceeds the threshold value when the sweep signal passes through the channel.

The two QAM systems both had error ratios in excess of the threshold levels which would result in errors being visible in the picture. The error ratios of the two VSB systems were below the threshold level and no errors would be visible in the picture. All of the modems showed zero errors with the Calan type low level sweep system.

Channel Change Time

The common usage of remote control devices for channel selection and the large number of TV channels available on cable has resulted in the sport of channel surfing where viewers rapidly tune through channels on the system to find one(s) they desire to watch. The picture must be displayed very shortly after channel selection or the subscriber is likely to become frustrated. The digital receivers are more elaborate than analogue receivers and, it is expected, will take longer to lock up and begin to deliver data. In addition, the MPEG decoder is expected to require about half a second to produce a picture after it begins receiving data, therefore, the time required for the receiver to lock up and begin delivering data must be kept to a minimum.

The 32-QAM receiver required 1.1 seconds to begin delivering data while the other three receivers required just over half a second.

Peak-to-Average Power Ratio

Signal power of a digital signal is normally specified as the average power measured within the 6 MHz channel while NTSC power is determined by measuring the power during the synchronization pulse. The digital signal, depending on the input data, will at times exceed the average power by some amount. The systems were measured to determine maximum peak-to-average ratio that could be expected 99.9% of the time. The peak signal levels determine the worst case distortion created by the digital signals and must be considered when determining operating levels and designing cable systems.

The 32-QAM signal peak-to-average ratio was 5.8 dB, the 8-VSB and 256-QAM peak-to-average ratio was 6.4 dB and the 16-VSB was 6.5 dB.

Burst Error

Digital systems use various techniques to minimize the impact of loss of data caused by ignition noise, intermittent power line noise, loose connections, etc. The implementation used in a system determines whether a receiver will tolerate a very brief interruption or one with a much longer period. The systems were tested by introducing high level noise for increasing periods of time at a 10 Hz rate until the threshold error ratio was obtained. A second test was then performed with the duration of the noise burst held at 20 µsec while the rate was increased until threshold was reached.

The 8-VSB system performed better than the 32-QAM system and the 16-VSB system worked better than the 256-QAM system. See Table 5 for complete results.

Table 5
Burst Noise Performance

	32 QAM	8 VSB	256 QAM	16 VSB
Burst length (µsec) @ rep rate (Hz)	60 @ 10	190 @ 10	27 @ 10	150 @ 10
Burst length (µsec) @ rep rate (kHz)	20 @ 1.5	20 @ 1.6	20 @ 0.03	20 @ 2.4

Data Rate

Both the QAM and the VSB systems offered a high data rate cable option. This option is intended to allow two ATV signals to be carried within one 6 MHz channel.

The data rate of the 32-QAM modem was 19.2 Mbps while the high data rate 256-QAM modem data rate was 38.2 Mbps. The data rate of the 8-VSB modem was 18.8 Mbps while the 16-VSB modem rate was 37.5 Mbps. Both high data rate modems accepted two standard data rate inputs and provided two standard data rate outputs.

CONCLUSIONS

The VSB systems performed better than the QAM signals in the majority of the tests. The theoretical performance of the two types of modulation formats is very close and details of each system's implementation determined which system operated better. The VSB implementation was better than the QAM implementation in the majority of the tests.

The FCC Advisory Committee's Technical Subgroup accepted the findings in the cable and broadcast lab tests and the Grand Alliance's own internal recommendation, which favored VSB modulation, and selected the VSB system as the transmission system for Advanced TV. The 8-VSB system will be used for terrestrial broadcast and cable distribution while the 16-VSB system will be used for cable transmission where the double data rate is deemed desirable or necessary.

The next steps in the selection of the advanced ATV system are to field test the VSB modems, then to build a complete encoder, modulator, receiver, and decoder and perform the appropriate lab and field tests on the complete system. As of the time of this writing, the modem field tests were scheduled to begin in April 1994 and the complete system lab tests are expected to take place in the fall of 1994 . Complete system field tests are to take place in the spring of 1995 with the final recommendation for the system occurring shortly after the field tests.

CableLabs will conduct the cable portion of each of the next three phases of ATV system testing, and will participate in the subsequent standard documentation process.