Progress on HDTV Broadcasting Standards in the United States

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Abstract: In the United States, the Federal Communications Commission (FCC) began a process six years ago to develop a terrestrial high definition television (HDTV) broadcasting standard. Early in 1993 a comprehensive report was released by the FCC's Advisory Committee on Advanced Television Service comparing five proposed systems that had undergone extensive testing. Although the report did not pick a "winning system," it did recommend that only digital systems receive further consideration as the United States standard. This paper presents comparisons and conclusions from that report and notes the recent formation of a "Grand Alliance" by the individual proponents of digital systems to propose a single system.

1. Introduction

The Advisory Committee on Advanced Television Service was formed by the Federal Communications Commission (FCC) in 1987 to assist the FCC in establishing an advanced television (ATV) standard for the United States.[1] The objective given to the Advisory Committee in its Charter by the FCC was:

> *The Committee will advise the Federal Communications Commission on the facts and circumstances regarding advanced television systems for Commission consideration of technical and public policy issues. In the event that the Commission decides that adoption of some form of advanced broadcast television is in the public interest, the Committee would also recommend policies, standards and regulations that would facilitate the orderly and timely introduction of advanced television services in the United States.*

Testing and data analysis on five high definition television systems recently were completed by the Advisory Committee. A report titled "ATV System Recommendation" was prepared by subgroups of the Advisory Committee giving results of the analyses and comparisons of the systems.[2] This paper summarizes that report with particular attention given to the technical conclusions.

Previously, the Advisory Committee approved a set of ten "Selection Criteria" for use in analyzing the performance of the systems tested and created a Special Panel that would use the criteria to evaluate the performance of tested ATV systems for the Advisory Committee's consideration. The ten criteria were grouped into three general categories:

- Spectrum Utilization
  - Service Area
  - Accommodation Percentage
- Economics
  - Cost to Broadcasters
  - Cost to Alternative Media
  - Cost to Consumers
- Technology
  - Audio/Video Quality
  - Transmission Robustness
  - Scope of Services and Features
  - Extensibility
  - Interoperability Considerations

On February 24, 1993 the Advisory Committee[3] met and adopted the "ATV System Recommendation" report which was completed by the Special Panel[4] during its meeting on February 8 - 11, 1993.

Section 2 of this paper is a summary of the findings and recommendations of the Special Panel. Section 3 gives a brief technical description of each of the five HDTV systems. Section 4 explains the Selection Criteria used by the Special Panel. Sections 5 (Spectrum Utilization), 6 (Economics), and 7 (Technology) give the detailed comparative information developed by the Special Panel. The paper concludes in Section 8 with a report on the recent formation of a "Grand Alliance" by the individual proponents of digital systems to propose a single digital system.

2. Special Panel findings and recommendations

Spectrum utilization findings

1. The analysis conducted by the Advisory Committee clearly demonstrates that a substantial difference exists in spectrum utilization performance between the analog Narrow-MUSE system and the four all-digital systems. The differences among the four digital systems generally are far less pronounced, however. Based on this analysis, it would appear that Narrow-MUSE will not prove to be a suitable terrestrial broadcasting ATV system for the United States.
2. The Special Panel notes that many system

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proponents have proposed improvements to their systems in the area of spectrum utilization. The Special Panel finds that the system improvements, primarily those identified by its Technical Subgroup as ready for implementation in time for testing, may lead to improvements in spectrum utilization and should be subjected to testing as soon as possible.

3. The Special Panel finds that the degree of interference from ATV-into-NTSC is recognized as an area of concern in certain markets. The Special Panel finds that the issue of ATV-into-NTSC interference, including interference to BTSC audio, should be addressed in the remaining stages of the system selection process, including the examination of refined allotment/assignment techniques, the study of possible beneficial effects of system improvements, and the consideration of any mitigations which might be achieved by transitional implementation policies.

Economics findings

1. No significant cost differences among the five proponent systems, either in costs to consumers or to broadcasters, are evident. Thus, based on cost alone, there is no basis to discriminate among systems. However, the additional benefits offered to broadcasters and others by the digital systems were noted as significant.

Technology findings

1. As a result of the testing process, the Advisory Committee is confident that a digital terrestrial advanced television system can provide excellent picture and sound quality. All of the system proponents have proposed refinements that are likely to enhance the audio and video quality beyond that measured in the testing process.
2. A variety of transmission formats was evaluated. The transmission robustness analysis conducted by the Advisory Committee clearly reveals that an all-digital approach is both feasible and desirable. All of the system proponents have proposed refinements that are likely to enhance robustness beyond that measured in the testing process.
3. An all-digital system approach is important to the scope of ATV services and features and in the areas of extensibility and interoperability. All four digital proponents have committed to a flexible packetized data transport structure and universal headers/descriptors. Progressive-scan/square-pixel transmission is considered beneficial to creating synergy between terrestrial ATV and national information initiatives. As well, scalability at the transmission data stream would permit trade-offs in "bandwidth on demand" network environments.

Special Panel recommendations

1. While all the proponents produced advanced television systems, the Special Panel notes that there are major advantages in the performance of digital HDTV systems in the United States environment and recommends that no further consideration be given to analog-based systems. The proponents of all four digital HDTV systems — DigiCipher, DSC-HDTV, AD-HDTV, and CCDC — have provided practical digital HDTV systems that lead the world in this technology. Because all four systems would benefit significantly from further development, the Special Panel does not recommend any one of these systems for adoption as a United States terrestrial ATV transmission standard at this time. Rather, the Special Panel recommends that these four finalist proponents be authorized to implement their improvements as submitted to the Advisory Committee and approved by the Special Panel's Technical Subgroup.
2. The Special Panel further recommends that the approved system improvements be ready for testing not later than March 15, 1993, and that these improvements be laboratory and field tested as expeditiously as possible. The results of the supplemental tests, along with the already planned field tests, would provide the necessary additional data needed to select a single digital system for recommendation as a United States terrestrial ATV transmission standard.

3. Description of the proposed systems

Narrow-MUSE

Narrow-MUSE, proposed by NHK, the Japan Broadcasting Corporation, uses analog pulse-amplitude-modulation transmission for the visual signal, and digital transmission for sound and auxiliary data. By pre-processing and filtering, an 1125-line interlaced format is converted to a 750-line interlaced format, and then the converted signal is encoded into the Narrow-MUSE format using the Multiple Sub-Nyquist Sampling Encoding method. The field rate is 60.0 Hz. Aspect ratio is 16x9. The baseband spectrum of the stream of pulse-amplitude-modulated pulses produced by the video encoder is divided into two portions. The low video frequencies, to 0.75 MHz, which carry most of the video power and also the synchronization information, are modulated via VSB-AM on a carrier located 200 kHz above the lower band edge. This carrier placement means that this portion of the Narrow-MUSE modulated signal is attenuated by the Nyquist filter in an NTSC receiver tuned to the same channel, thus limiting interference into NTSC receivers. The high video frequencies (from 0.75 MHz up), which represent the fine detail in the Narrow-MUSE picture, are modulated via SSB-AM, occupying a band extending from 1.42 MHz to approximately 6 MHz above the lower band edge. A gap in the spectrum from 1.1 MHz to 1.42 MHz is designed to minimize interference to and from co-channel NTSC. The Narrow-MUSE system has four channels of audio with 15 kHz bandwidth per channel. A near-instantaneous companding DPCM method is used for the audio. The audio is sampled at 32 kHz with 15 bit precision. Audio and auxiliary information are coded into ternary symbols for digital transmission.

DigiCipher

DigiCipher, proposed by the American Television Alliance (General Instrument Corporation and the Massachusetts Institute of Technology), is a digital simulcast system that requires a single 6 MHz television transmission channel. The DigiCipher video source is an analog RGB signal with 1050 lines, 2:1 interlaced, a 59.94 Hz field rate, and an aspect ratio of 16:9. The video sampling frequency is 53.65 MHz. The image in a single frame consists of 960 lines of 1408 pixels. Chrominance information is subsampled horizontally by a factor of 4, and vertically by a factor of 2 by discarding every second field. The system uses motion compensated predictive coding with a Discrete Cosine Transform (DCT) and Huffman coding. The video encoder uses four independent coders, each working on one-fourth of the image (full height and one-fourth width). The system features adaptive field/frame coding and progressive PCM refresh with the one-fourth width panels moving continuously to the left. Two transmission modes are supported: 32 QAM, the primary transmission mode, and 16 QAM, both with a symbol rate of 4.88 M-symbols per second. The 32 QAM primary mode has a video data rate of 17.47 Mbits/sec and a total transmission rate of 24.39 Mbits/sec. Concatenated trellis coding, Reed-Solomon block coding, and adaptive equalization are used to protect against channel errors. The DigiCipher system provides 4 digital audio channels using Dolby Laboratories AC-2 compression system. The audio is sampled at 48 kHz with 16-bit precision. The compressed audio rate is 252 kbits/sec per pair of channels. The system also provides 126 kbits/sec of data capacity and 126 kbits/sec for control such as subscriber addressing.

Digital Spectrum Compatible HDTV (DSC-HDTV)

DSC-HDTV, proposed by Zenith and AT&T, is a digital simulcast system that requires a single 6 MHz television transmission channel. The video source is an analog RGB signal with alternate 787/788 lines, progressively scanned, a 59.94 Hz frame rate, and an aspect ratio of 16:9. The display format is 720 lines by 1280 pixels per line. The video sampling frequency is 75.3 MHz. Chrominance signals are decimated by a factor of two both horizontally and vertically. Nine-bit precision is employed for all luminance and chrominance samples. The video compression includes perceptual coding, vector quantization, and adaptive fractional leak. Motion is estimated by hierarchical block matching with 1/2 pixel accuracy. A displaced frame difference (DFD) is computed and transformed with a Discrete Cosine Transform (DCT). Block sizes for motion compensation, varying from 32H x 16V to 8 x 8, are adapted spatially to places in the image providing the most benefit. Time division multiplexing between 4-level and 2-level VSB transmission is employed to provide improved error performance and extended coverage. The amount of time at each level depends on the complexity of the image being processed, with more complex images requiring more 4-level data. To provide a measure of "graceful degradation," certain critical data are always transmitted in the more rugged 2-level mode. In addition to the Standard Mode, the DSC-HDTV system also offers a Robust Mode, which increases the ratio of 2-level to 4-level data that is transmitted. The variable length codes are packed into slices (64H x 48V) with a header providing identification of the first slice boundary in each segment to allow restart of the variable length decoding. Transmission is by vestigial sideband modulation with a pilot carrier 0.31 MHz above the lower edge of the 6 MHz channel. Video data rate ranges from 8.45 to 16.92 Mbits/sec and the total transmission rate ranges from 11.14 to 21.0 Mbits/sec. The system employs a post-comb-filter in the receiver which automatically switches in to minimize the effects of NTSC co-channel interference. The DSC-HDTV system provides four digital audio channels using Dolby Laboratories AC-2 compression system. The audio is sampled at 47 kHz, the horizontal scan rate, with 16 bit precision. The compressed audio rate is 252 kbits/sec per pair of channels. One pair is transmitted as 2-level data and the other as 4-level data. The system also provides 413 kbits/sec of data capacity in two separate ancillary data channels.

Advanced Digital HDTV (AD-HDTV)

AD-HDTV, proposed by the Advanced Television Research Consortium (ATRC), is a digital simulcast system that requires a single 6 MHz television transmission channel. The ATRC includes: David Sarnoff Research Center, North American Philips, Thomson Consumer Electronics, NBC, and Compression Labs, Incorporated. The AD-HDTV video source is an analog RGB signal with 1050 lines, 2:1 interlaced, a 59.94 Hz field rate, and an aspect ratio of 16:9. A matrix converts the RGB color signals to Y-Cr-Cb components, conforming to the SMPTE 240M representation and colorimetry specification. The luminance video sampling frequency is 56.64 MHz. The source and display format is interlaced with 960 lines by 1500 pixels per line. To create the internal progressive scan format used by the system's frame based coding, the interlaced source is transcoded into a 960 line by 1248 pixels per line, progressively scanned, 29.97 frames per second format. After format conversion, the two color-difference signals are decimated by a factor of two both horizontally and vertically, resulting in a sampling density one fourth that of the luminance signal. The video compression uses an adaptation of the MPEG-1 (Moving Picture Experts Group) standard. The system uses two separate transmission channels, each with 32 QAM modulation, totaling 24 Mbits/sec. The high priority (HP) channel carries 4.8 Mbits/sec of data and is of higher power than the standard priority (SP) channel with 19.2 Mbits/sec of data. The purpose of the two-channel approach is to provide a measure of "graceful degradation" and to reduce co-channel interference from and into NTSC. The audio channels are compressed using a proprietary standard called MUSICAM that is related to layers 1 and 2 of the 3-layer MPEG audio standard. The audio is sampled at 48 kHz with 16 bit precision. Audio in the tested system supported two stereo pairs of 256 kbits/sec each; they were transmitted in the HP channel. An additional 256 kbits/sec was provided for data.

Channel Compatible DigiCipher (CCDC)

CCDC, a second system proposed by the American Television Alliance (Massachusetts Institute of Technology and General Instrument Corporation), is a digital simulcast system that requires a single 6 MHz television transmission channel. The video source is an analog RGB signal with alternate 787/788 lines, progressively scanned, a 59.94 Hz frame rate, and an aspect ratio of 16:9. A matrix converts the RGB color signals to YUV signals. The display format is 720 lines by 1280 pixels per line. The video sampling frequency is 75.52 MHz. Chrominance signals are decimated by a factor of two both horizontally and vertically, resulting in a sampling density of one fourth that of the luminance signal. Eight-bit precision is employed for all luminance and chrominance samples. The video compression uses an adaptive form of motion-compensated predictive coding in which prediction differences are spatially transformed using a Discrete Cosine Transform (DCT). A selected subset of the resultant transform coefficients is entropy coded to represent the image that will be reconstructed at the receiver. Information related to the compressed video is entropy coded for transmission, including motion vectors and parameters related to decisions on intra-frame and inter-frame coding. The video encoder uses four processors, each working on one-fourth of the image (full height and one-fourth width panels), with intra-frame refresh moving continuously from right to left. Two transmission modes are supported: 32 QAM, the primary transmission mode, and 16 QAM, both with a symbol rate of 5.29 M-symbols per second. The 32 QAM primary mode has a video data rate of 18.88 Mbits/sec and a total transmission rate of 26.43 Mbits/sec. Concatenated trellis coding, Reed-Solomon block coding, and adaptive equalization are used to protect against channel errors. The CCDC system provided six independent digital audio channels using the MIT Audio Coder system for compression. The audio is sampled at 48 kHz. The compressed audio rate is 252 kbits/sec per pair of channels. In addition, a combined auxiliary and control data capacity of 252 kbits/sec is provided.

4. The selection criteria

The Selection Criteria constitute the key issues that must be examined in order to recommend an ATV system. Each of the proposed systems was measured against the Selection Criteria and compared with one another in these key areas to determine the best system.

Spectrum utilization criteria

Service area

The service area of a NTSC television station is defined as the area within the station's Grade B contour reduced by the interference within that contour. For an ATV station, service area is defined as that area contained within the station's noise-limited contour reduced by the interference within that contour.

Coverage area is not the same as service area. The coverage area of a NTSC television station is defined as the area within the station's Grade B contour without regard to interference from other television stations which may be present. For an ATV station, coverage area is defined as the area contained within the station's noise-limited contour without regard to interference which may be present.

Accommodation percentage

Accommodation percentage is the percentage of existing NTSC stations that can be accommodated with an additional simulcast ATV channel (independent of the resulting service area).

Economics criteria

Cost to broadcasters

In this paper, cost to broadcasters is defined as the equipment cost for a broadcast station to deliver a simulcast terrestrial ATV signal. It does not include the cost of in-house production.

In implementing ATV, broadcasters will incur costs of new studio equipment such as ATV encoders and monitors, router/switchers and video recorders; new transmission equipment such as ATV broadcast transmitters, ATV antennas, transmission lines and studio-to-transmitter links; and possibly other new equipment.

A "transitional" station is defined as one that provides the ability to "pass through" the signals of a network or syndicated program source with essentially the same production values in the program integration as today. The transitional station has the ability to upgrade easily to more extensive ATV operations and to higher levels of performance as dictated by audience growth and station finances.

A "minimal" station is defined as one that provides the ability to "pass through" the signals of a network or syndicated program source with compromises made in its capabilities in order to reduce costs to a minimum. The minimal station will not bear the costs associated with providing for future upgrades and might require replacement if an upgrade is needed.

Cost to alternative media

Cost to alternative media is defined as the equipment cost for a cable system operator, or other alternative service provider, to deliver an ATV signal.

Information on this topic was not available at the time of the Special Panel meeting.

Cost to consumers

Cost to consumers, in this paper, is defined as the price of a consumer ATV receiver and is based on the estimated material cost.

Technology criteria

Audio/video quality

Video quality is defined as the inherent and received quality of the picture, as subjectively perceived by non-expert viewers, supplemented by objective characterization and performance data, including expert viewer results.

Audio quality is the inherent sound quality as subjectively perceived by expert listeners, and supplemented as necessary by objective characterization and performance data.

Transmission robustness

Transmission robustness is defined as the ability of a transmission system to maintain a useful received picture, sound, and data in the presence of co-channel, adjacent-channel, taboo channel, and discrete frequency interference; and such impairments as noise, multipath, airplane flutter, etc., for terrestrial broadcasting; and second and third order distortion, phase noise, etc., for cable transmission.

Scope of services and features

Scope of services and features addresses the need of an ATV system to support an array of services, features and capabilities beyond the program video and audio.

Some capabilities covered here are features of the overall system. These include details of the picture and sound performance near the edge of coverage, the ability to operate in different modes of robustness versus picture quality, and the ability to reallocate channel capacity on demand among video, audio and ancillary services.

Other capabilities are specific features of the picture coding, sound coding or ancillary data capacity, other than quality or robustness. These include the support of various multi-channel sound formats, services for viewers with special needs, and the ability to support inexpensive receivers with NTSC-quality video.

Extensibility

Extensibility is the ability of a transmission system to support and incorporate extended functions and future technology advances.

Interoperability considerations

Interoperability considerations address the suitability of a transmission system for operation on a variety of media, in addition to terrestrial broadcasting. They include delivery over alternate media such as cable, satellite, VCR, and packet networks; transcoding with NTSC, film, and other video standards; integration with computers and interactive systems; and scalability and the use of headers/descriptors to accommodate a variety of applications.

5. Spectrum utilization comparisons

Two spectrum utilization selection criteria were compared: accommodation percentage and service area. "Accommodation percentage" specifies the fraction of existing NTSC television stations that could be assigned an ATV channel. "Service area" refers to the interference-limited coverage area of new ATV stations.

The analysis of spectrum usage of the proposed systems employed an allotment approach developed by the FCC staff and a service and interference model developed by a working party of the Advisory Committee. Combining the two permitted the development of approximately optimum allotment/assignment plans and comparison of service expected to be provided by each system, if implemented, with service provided by the NTSC system currently in use.[5]

The plan seeks, station-by-station, to match or exceed current interference-limited NTSC service area with future companion ATV service area. To the extent possible, the ATV service area for each station is optimized to provide for interference-free ATV service to any area that is served interference-free by the companion NTSC station. The analysis includes consideration of vacant noncommercial allotments as well as authorized stations and pending applications.[6] Station locations and antenna heights above average terrain are assumed to be the same for the NTSC and ATV services. Other input parameters to the program are the planning factors applicable to all ATV systems (see 1) and factors specific to each ATV system (see 2) as determined by the test programs at the Advanced Television Test Center (ATTC) and Advanced Television Evaluation Laboratory (ATEL).

An initial NTSC program run provided the reference for each of the ATV systems tested. The program output includes Grade B coverage area and interference-limited service area for each of the 1,657 authorized and applied-for television facilities in the August 1, 1992 FCC data base. Interference-limited NTSC service areas were determined on the basis of a co-channel desired-to-undesired (D/U) ratio of 28 dB and first adjacent D/U ratios of -6 dB for interference from the lower adjacent-channel and -12 dB for interference from the upper adjacent-channel. Taboo considerations are based on interference threshold of visibility (TOV) data from ATTC. Subjective tests at ATEL of co-channel interference from NTSC to NTSC showed that a 28-dB co-channel ratio corresponded to

	Low VHF	High VHF	UHF
Antenna Impedance (ohms)	75.0	75.0	75.0
Bandwidth (MHz)	6.0	6.0	6.0
Thermal Noise (dBm)	-106.2	-106.2	-106.2
Noise Figure (dB)	10.0	10.0	10.0
Frequency (MHz)	69	194	615
Antenna Factor (dBm/dBu)	-111.7	-120.7	-130.7
Line Loss (dB)	1.0	2.0	4.0
Antenna Gain (dB)	4.0	6.0	10.0
Antenna F/B Ratio (dB)*	10	12	14

* In addition to F/B ratio, a formula is employed for the forward lobe simulating an actual receiving antenna pattern.

Figure 1. Receiver planning factors applicable to all ATV systems.

a CCIR impairment rating of 3 for NTSC stations using precise offset.[7] Accordingly, co-channel interference from ATV to NTSC is based on impairment grade 3 also. NTSC receiving antennas beyond the City Grade Contour are assumed to have a front-to-back (F/B) ratio of 6 dB. No directivity is assumed for receiving antennas within the City Grade Contour. NTSC service is based on median f(50,50)[8] signal strength. f(50,10) propagation data are used for both NTSC and ATV interfering signals.

The outer limit of NTSC service, in the absence of interference, is considered to be the Grade B level. As specified by the FCC, the median field strengths corresponding to Grade B are: 47 dBu for low VHF, 56 dBu for high VHF, and 64 dBu for UHF.

The outer limit of ATV service in the absence of interference is that determined by the carrier-to-noise ratio yielding a CCIR impairment grade of 4. For digital systems, the f(50,90) signal strength is used for noise and interference-limited service calculations.

The analysis was conducted under two allotment scenarios (using both VHF and UHF channels for ATV stations, and using only UHF channels) and two sets of interference constraints (considering only co-channel interference, and both co-channel and adjacent-channel interference). In addition, the impact of taboos was assessed by recalculating coverage and interference for each scenario assuming the taboo performance measured in the laboratory. The Advisory Committee's Working Party on Spectrum Utilization determined that the analysis should be considered in the following priority order: 1) co-channel and adjacent-channel interference, 2) only co-channel interference, and 3) co-channel, adjacent-channel and taboo interference.

While the analysis that includes taboo performance maximizes consideration of interference impacts, limitations in both test and analysis involving taboos cause the results to have more limited value. During test, measurements were taken at TOV, yielding overly stringent results. Further, maximum amplitude limitations of the laboratory test facility affected the completeness of taboo test results. Finally, the effect of taboo interference is exaggerated in the computer analysis because taboo performance was not used to optimize allotments/assignments.

The analysis that includes both co-channel and adjacent-channel interference maximizes interference considerations short of including taboos. Adjacent-channel performance reflects both system and tuner design considerations. Thus, to the extent that a proponent's tuner, as tested, was suboptimal, adjacent-channel performance of ATV may have been negatively impacted.

Considering only co-channel interference removes all adjacent-channel constraints resulting in a different

CARRIER-TO-NOISE	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
	+38	+16.0	+16.0	+18.4	+15.4

CO-CHANNEL	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
ATV-into-NTSC	+16.8	+35	+35	+34	+36
NTSC-into-ATV	+21	+7.6	+3.5	+0.50	+8.1
ATV-into-ATV	+31	+16.4	+18.2	+19.1	+16.6

ADJACENT-CHANNEL	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
Lower ATV-into-NTSC	-31	-13.5	-17.2	-16.0	-17.8
Upper ATV-into-NTSC	-12.0	-21	-7.5	-8.9	-17.0
Lower NTSC-into-ATV	+28	-30	-43	-38	-37
Upper NTSC-into-ATV	-11.8	-24	-42	-36	-37
Lower ATV-into-ATV	-15.5	-23	-35	-33	-32
Upper ATV-into-ATV	+16.6	-23	-36	-16.8	-32

Figure 2. System-specific planning factors (D/U in dB).

assignment table. Tuner design is not a direct consideration for this case.

In all instances it should be noted that no reassignment or power adjustment was attempted for the purpose of reducing new interference into NTSC, or for the purpose of maximizing ATV service area.

Accommodation percentage

With the exception of one system — Narrow-MUSE — allotment/assignment schemes could be created to accommodate 100% of existing NTSC broadcast stations. Narrow-MUSE allotment/assignment plans accommodated 77.2% or 73.7% under the VHF/UHF and UHF-only channel availability options, respectively. Tradeoffs exist in the process of allotting ATV channels. While attempts were made to match the ATV coverage with that of companion NTSC stations, the provision of ATV allotments was accomplished by reducing ATV coverage areas for some stations and introducing some new interference to the coverage areas of a portion of the set of existing NTSC stations. The severity of the consequences of these tradeoffs are considered in the next section in which systems are grouped based on service area and interference performance.

Service area

System performance groupings have been made based on three factors: ATV service area during the transition from NTSC to ATV, ATV service area after the transition period ends, and ATV-into-NTSC interference during the transition period. These groupings are summarized in 3. 4 depicts the interference-limited service area of each ATV station, during the transition period, relative to the interference-limited service area of its companion NTSC station under the VHF/UHF Scenario and under the UHF Scenario, taking into account both co-channel and adjacent-channel constraints. In this graph, the 1,657 current NTSC stations are placed in order of decreasing ATV to NTSC service area ratio. Examination of the graphs reveals that about 1200 of the ATV stations would have an ATV service area equal to or greater than the size of their companion NTSC service area with any one of the four digital ATV systems.

Examination of the ATV coverage during and after the transition revealed that the performance of the DSC-HDTV and CCDC systems was slightly better than the DigiCipher and AD-HDTV systems. The performance of the Narrow-MUSE system in this category was significantly worse than the four all-digital systems.

With regard to ATV interference into NTSC, the performance of the DigiCipher, DSC-HDTV and CCDC systems was judged slightly better than the AD-HDTV system.

The Special Panel also recognized that the degree of interference from ATV-into-NTSC, as reflected in the test results and the Working Party on Spectrum Utilization report, is an area of significant concern in certain markets; however, the practical extent of this interference is not known. The Special Panel noted that the computer allotment/assignment model was designed for the purpose of comparing competing ATV systems, not for generating optimum allotment tables. As indicated above, because the allotment/assignment plans attempted to maximize ATV coverage area, the result produced some new NTSC interference areas. Thus, a plan which reduced ATV coverage by some small degree from the existing plan could minimize or eliminate new NTSC interference.

It also should be noted that the analysis did not take into account interference into BTSC audio service. Future analysis should include this relevant test data.

Accordingly, the Special Panel believed that the Advisory Committee should direct that the issue of ATV-into-NTSC interference be addressed in the remaining stages of the system selection process. This further study could include the gathering of additional data through laboratory tests of system improvements, field tests and/or special post-recommendation tests, and the use of refined allotment/assignment techniques.

6. Economic comparisons

Cost to broadcasters

Estimated costs were developed for both "transitional" stations and "minimal" stations. It was assumed that the station's existing tower has sufficient capacity for installation of the new ATV antenna and transmission line and that the station's equipment space has room for additional gear without the need to add floor space, racks, power distribution, air conditioning, or other support services. Similarly, it was assumed that stereo audio facilities already exist in the station. Additionally, the analysis was based on the use of a compressed NTSC signal multiplexed into the same STL with the ATV signal, as opposed to construction of a totally new and separate microwave path to the transmitter.

Stations With ATV Service Area Equal To or Greater Than NTSC (%)	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
VHF/UHF Co- & Adjacent-Channel	7.1	71.9	87.4	77.4	83.2
UHF Co- & Adjacent-Channel	5.9	70.2	80.3	73.3	76.7

ATV Stations With No ATV or NTSC Interference (%)	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
VHF/UHF Co- & Adjacent-Channel	8.6	42.4	59.9	46.5	54.1
UHF Co- & Adjacent-Channel	7.8	45.7	54.3	46.8	51.5

ATV Stations With 35% of Coverage Area Having ATV or NTSC Interference (%)	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
VHF/UHF Co- & Adjacent-Channel	61.6	4.2	1.3	3.4	1.8
UHF Co- & Adjacent-Channel	64.0	4.6	3.0	5.3	3.0

ATV Stations With No ATV Interference (%)	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
VHF/UHF Co- & Adjacent-Channel	16.4	60.2	71.7	55.2	72.3
UHF Co- & Adjacent-Channel	14.2	60.3	64.8	52.7	66.1

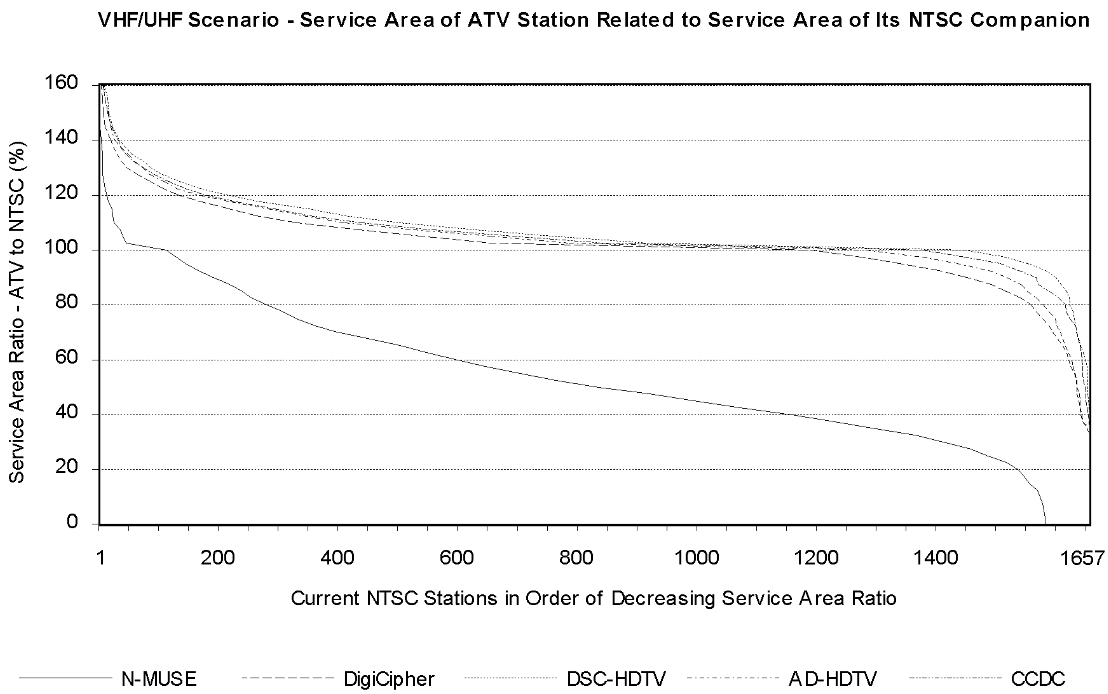
ATV Stations With 35% of Coverage Area Having ATV Interference (%)	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
VHF/UHF Co- & Adjacent-Channel	49.5	1.8	1.1	3.2	0.8
UHF Co- & Adjacent-Channel	52.7	3.0	2.9	5.2	2.1

NTSC Stations With No ATV Interference (%)	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
VHF/UHF Co- & Adjacent-Channel	74.4	60.1	58.2	55.7	59.4
UHF Co- & Adjacent-Channel	77.7	62.9	61.1	59.7	62.3

NTSC Stations With 35% of Coverage Area Having ATV Interference (%)	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
VHF/UHF Co- & Adjacent-Channel	0.5	2.1	2.4	2.8	2.3
UHF Co- & Adjacent-Channel	0.2	7.8	8.0	9.7	8.7

New NTSC Interference (million square kilometers)	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
VHF/UHF Co- & Adjacent-Channel	0.78	1.41	1.51	1.77	1.54
UHF Co- & Adjacent-Channel	0.77	2.12	2.26	2.51	2.29

Figure 3. ATV service area, ATV interference, and NTSC interference calculated in the analysis.



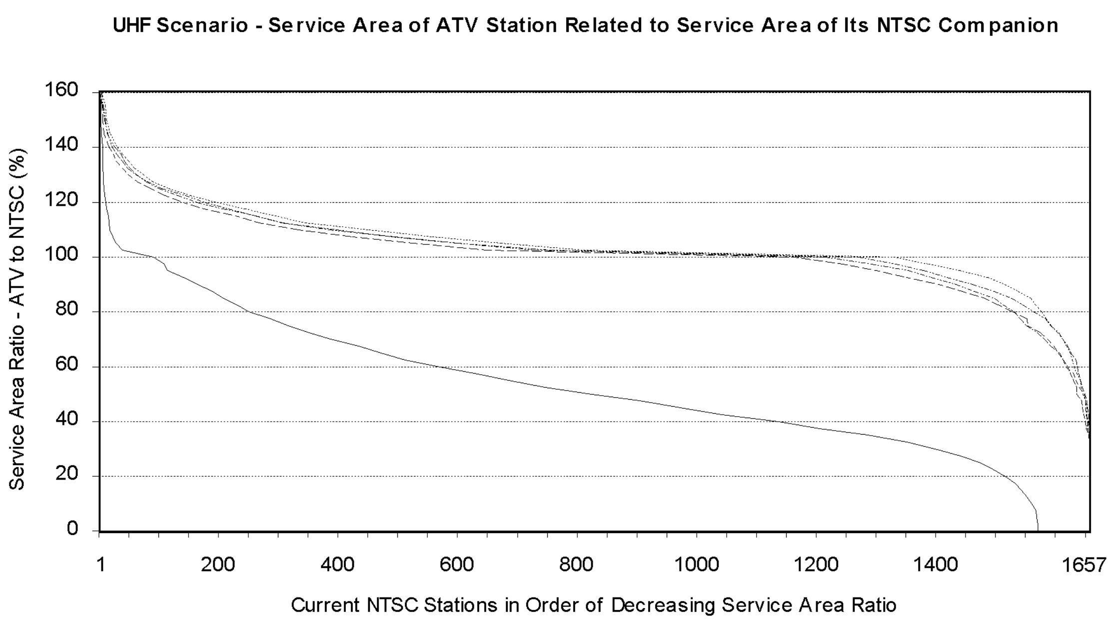


Figure 4. Interference-limited service area of each ATV station relative to the interference-limited service area of its companion NTSC station (co-channel and adjacent-channel constraints).

A cost was developed for each item on a station block diagram for each of the proposed ATV systems. Where possible, the likely cost of an item was sought through surveys of manufacturers likely to produce that item. In the many cases where it was not possible to obtain expected costs of items from manufacturers or from comparable equipment in the marketplace, broadcast system designers estimated selling prices based on the relative complexity of the items.

The estimated equipment costs for the transitional station is shown in 5 for each of the proposed systems.

Cost to consumers

Costs were estimated for 34" widescreen direct view receivers and 56" widescreen projection receivers. The estimates were based on a common format to compare the technical complexity and material costs of receivers for each of the proposed systems. It was assumed that 1998 would be the time when mass production of HDTV receivers would reach 1 million units. Costs were estimated consistent with technology predictions for 1998.

It was generally recognized that the cost of the display would have a major impact on the cost of the receiver and that, therefore, the market study would be influenced by that cost more than by any other. As a result, considerable effort was expended to find accurate estimates.

The proponents provided block diagrams, gate counts, and pin counts for a suggested chip set for their systems. The digital IC information provided by all proponents was entered into the FAIRCOST II program for equivalent cost estimates. This program was developed for the IC industry and provides reasonably accurate cost predictions for ICs.

Other costs, such as audio amplifiers and speakers, circuitry for NTSC processing, and cabinets, were assumed the same for all proposed systems.

The estimated material cost data for 34" widescreen CRT receivers are shown in 5 for each of the proposed systems . The estimated material cost data for 56" widescreen projection receivers are shown in 5 for each of the proposed systems. The estimated retail prices for the receivers, assuming the retail price is 2.5 times the material cost, are shown also.

Economics findings

There were some nominal cost differences among the systems in both the estimated costs to consumers and broadcasters, as noted previously. However, these differences in costs are of a minor magnitude and thus judged to be indistinguishable.

SUBSYSTEM	Cost (thousands)				
	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
Satellite Receiver, Demodulator, Decoder	$ 13.5	$ 13.5	$ 13.5	$ 13.5	$ 13.5
Character Generator, Still Store, Two 28" Monitors	200.0	200.0	200.0	200.0	200.0
Routing Switcher (10 x 10), Master Control	125.0	125.0	125.0	125.0	125.0
2 VTRs and Monitors	170.0	170.0	170.0	170.0	170.0
NTSC Upconverter	19.0	19.0	24.0	19.0	24.0
ATV-to-NTSC Downconverter	15.0	15.0	20.0	15.0	20.0
34" Monitor, Seven 17" Monitors, Eight Decoders	110.0	110.0	119.0	110.0	119.0
Encoder	200.0	200.0	240.0	280.0	220.0
STL Subsystem	92.5	92.5	92.5	92.5	92.5
Modulator, Exciter	25.0	30.0	30.0	35.0	30.0
Transmission Subsystem	740.7	725.5	725.5	725.5	725.5
TOTAL COST	$1,710.7	$1,700.5	$1,759.5	$1,785.5	$1,739.5

Figure 5. Equipment cost for a transitional station.

SUBSYSTEM	Material Cost				
	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
Signal Processing Components	$ 168	$ 98	$ 116	$ 127	$ 124
Audio Amplifiers, Speakers	30	30	30	30	30
Scan System, Power Supply, Video Amps	60	60	73	63	73
Display	700	700	700	700	700
Cabinet	90	90	90	90	90
TOTAL MATERIAL COST	$1,048	$ 978	$1,009	$1,006	$1,017
ESTIMATED RETAIL PRICE	$2,620	$2,445	$2,523	$2,515	$2,543

Figure 6. Material cost data for a 34" widescreen direct view receiver.

7. Technology comparisons

The Special Panel examined five selection criteria (of the overall ten) under the heading Technology: Quality, Transmission, Scope of Services and Features, Extensibility, and Interoperability Considerations. These particular criteria are all closely bound up in the specific technologies employed in the various ATV system designs. This section sets forth the Special Panel's analysis and conclusions regarding these technical criteria.

Of the five selection criteria, the first two — quality and transmission, were based on actual system testing. The other three were primarily the subject of detailed analyses of the systems as certified.

The Special Panel concluded that four excellent digital HDTV systems were developed as the result of this process. Digital ATV transmission is completely viable for over-the-air broadcasting and for transmission by the alternative media of cable and satellite. The overall picture quality of two systems came remarkably close to the quality of the 1125-line high-definition studio reference.

However, the extensive measured data and subjective assessments of the systems nevertheless revealed the magnitude of the challenges associated with achievement of high overall picture and sound quality, while also ensuring adequate coverage, transmission robustness, and acceptably low interference in a simulcast environment — all within the bounds of a reasonable average effective radiated power.

The Special Panel's examination further revealed that there are likely to be pragmatic tradeoffs required between the fundamental ATV requirements (under the criteria quality and transmission) and the sometimes conflicting but desirable capabilities described in the criteria of scope of services and features, extensibility and interoperability.

This portion of the report summarizes the comparative results determined by the Special Panel for each of the five technological criteria. The panel

SUBSYSTEM	Material Cost				
	N-MUSE	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
Signal Processing Components	$ 168	$ 98	$ 116	$ 127	$ 124
Audio Amplifiers, Speakers	30	30	30	30	30
Scan System, Power Supply, Video Amps	176	176	201	176	201
Display	1,050	1,050	1,050	1,050	1,050
Cabinet	140	140	140	140	140
TOTAL MATERIAL COST	$1,564	$1,494	$1,537	$1,522	$1,545
ESTIMATED RETAIL PRICE	$3,910	$3,735	$3,843	$3,805	$3,863

Figure 7. Material cost data for a 56" widescreen projection receiver.

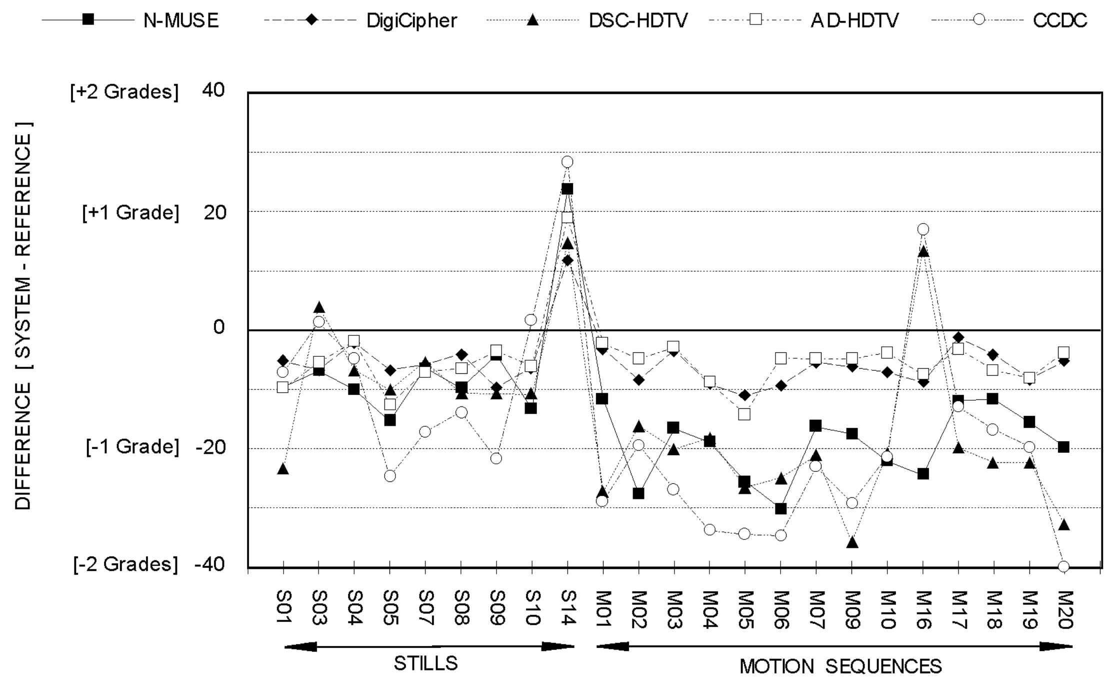


Figure 8. Average differences between quality judgments for the 1125-line studio quality reference and for each of the proposed ATV systems.

also agreed on key findings for each of these selection criteria. These findings recognize the degree of conflict among many listed attributes. The Special Panel emphasized the importance of these findings as guidelines to those system proponents who seek to revise and improve their system design.

Audio/video quality

Video quality

The image quality achieved by the systems under ideal conditions, and under other circumstances relevant to the quality of the received image, was determined in a number of tests involving judgments by experts and by non-experts.

Transmission of ATV in the 6-MHz channel inevitably requires compression of the video data. This process introduces picture-related impairments in that small number of images and image-sequences which stress the compression scheme used. The designer therefore must optimize the scheme to handle the range of material likely to be transmitted, while ensuring that, under worst-case conditions, the impairments introduced are minimally objectionable.

In Basic Received Quality, DigiCipher and AD-HDTV were judged, on average, only about 0.3 CCIR grades lower in quality than the 1125-line studio reference for most segments of test material; the other systems exhibited lower performance (see 8). However, all systems exhibited visible weaknesses in one or more tests designed to address other matters relating to quality (e.g., noisy source material, multiple encode/decode operations, etc.).

For still material, the ATV systems did not differ significantly overall. For live video and for film, however, the DigiCipher and AD-HDTV systems exhibited significantly better performance than the other systems. For a graphic sequence that stressed vertical and temporal performance, the DSC-HDTV and CCDC systems performed best.

For noisy source material, the DigiCipher and AD-HDTV systems performed significantly better than the other systems. For scene cuts, the AD-HDTV system performed best. For material subjected to concatenated encode/decode operations, the DigiCipher system performed best. For material designed to stress the source-coding algorithms of the four all-digital systems, the DigiCipher and CCDC systems performed best. And, finally, examinations of quality achieved under extended coverage conditions (made only for Narrow-MUSE, DSC-HDTV, and AD-HDTV) revealed a clear superiority for the Narrow-MUSE system.

Overall, these results show a clear advantage for the DigiCipher and AD-HDTV systems in terms of video quality. However, they also point to the necessity for improvement, even in the two leading systems.

In interpreting the results, three mitigating factors should be considered. First, the video and film material used in tests of the progressively scanned ATV systems (i.e., DSC-HDTV and CCDC) exhibited high levels of random noise, as well as horizontally coherent noise. Although this may have affected adversely the performance of these two systems, it is not possible to quantify the extent to which their performance would have been affected. Second, it is likely that all systems suffered from deficiencies in the prototype hardware brought to test. And, finally, since the time of test, all system proponents claim to have made improvements in image quality.

Video quality findings

1. The DigiCipher and AD-HDTV systems showed an overall advantage over other systems. However, all systems exhibited weaknesses in tests designed to assess the quality of the received image.
2. Since the time of test, all systems have declared refinements that may have implications for image quality. The impact of these refinements, which may be significant for the selection of an ATV standard, cannot be established without further laboratory testing. These improvements must be fully implemented before such tests.
3. In advance of any further testing, system proponents should attempt to improve Basic Quality and to minimize the occurrence of visible impairments. As well, proponents should give due consideration to performance on other matters relating to the quality of received image (e.g., source noise, concatenated processing, diverse program material, and momentary signal fades). Existing test plans and test materials should be reviewed and, if necessary, enhanced to ensure consideration of these issues.
4. Excellent image quality is fundamental to success in providing HDTV programming. The ability to achieve this, without jeopardizing the viability (e.g., coverage) of ATV and NTSC broadcast service, should be given the most serious attention.
5. It is to be expected that, as technologies mature, techniques for image compression will improve. It is essential that the system ultimately selected allow for compatible enhancements in image coding and for efficient re-deployment of any capacity thereby made free.
6. The systems tested were based on two different image scanning approaches: interlaced and progressive scanning. The choice of an approach is a complex trade-off of factors at capture, processing, and display. These factors include: efficiency at capture (e.g., camera sensitivity), static and dynamic resolution, accuracy of motion estimation in processing, inter-field/inter-line artifacts at display, etc. Information is urgently needed concerning optimum trade-offs at various stages in the television chain, given practical considerations such as data rate and cost.

Audio quality

The sensitivity of the audio subjective test results was impaired by many irregularities including high variability and inconsistency among the judges. A special audio Task Force reviewed the data and the corresponding audio test tapes, and recommended against the use of the data in this report. The Task Force observed, however, that even though in some instances audio point of unusability (POU) was not determined under conditions with transmission impairment, there was no evidence that audio failed before the accompanying video in any system.

Traditional audio objective tests were conducted for frequency response, dynamic range, THD, THD+N and IMD. AD-HDTV objective audio tests were not performed due to that system's late arrival for testing. In the objective tests, that of the CCDC audio system yielded measurement data which were significantly better than that of Narrow-MUSE, DigiCipher, or DSC-HDTV. Caution is advised in the interpretation of objective measurements of these compressed digital audio systems because sophisticated perceptual audio coding techniques can cause them to be quite misleading.[9]

System improvements for DigiCipher and DSC-HDTV include the implementation of ATSC document T3/186 audio features including 5.1 channel sound, incorporating two Dolby Laboratories AC-3 encoders for DigiCipher and an AC-3 encoder for DSC-HDTV. DigiCipher will incorporate a single AC-3 decoder while DSC-HDTV will incorporate both an AC-3 decoder and a 2-channel AC-2A decoder. System improvements for AD-HDTV include the implementation of T3/186 audio features including 5 channel sound. If the MUSICAM based 5-channel system is defined in time for implementation before further testing, AD-HDTV will incorporate it. If not, another unspecified multichannel system will be utilized. Dual mode composite and independent coding will be implemented in DigiCipher; DSC-HDTV will have both composite and independent channel coding, while independent coding of six channels has been implemented in CCDC.

Audio quality findings

1. Audio subjective tests of the new multichannel audio systems should be conducted, preferably in compliance with recent CCIR subjective test recommendations.
2. The desirability of composite versus independent channel coding should be examined.
3. Complete audio systems should be implemented in hardware before further testing is conducted on any system.

Transmission robustness

Noise performance

The carrier-to-noise ratio (C/N) at the TOV for this impairment is listed below for each of the digital systems:

DigiCipher	16.0 dB
DSC-HDTV	16.0 dB
AD-HDTV	18.4 dB
CCDC	15.4 dB

For analog Narrow-MUSE, a subjective impairment rating of 4.0 (perceptible, but not annoying) was obtained at C/N = 38 dB.

The Special Panel concluded that the digital systems have a significant advantage over the analog system for this attribute. Among the digital systems, a 2-3 dB difference in threshold performance is significant. Therefore, the threshold C/N performance of DigiCipher, DSC-HDTV, and CCDC is significantly superior to that of the other systems.

Static multipath

Ability to tolerate discrete, static echoes was measured at several delay times, ranging from -0.08 microseconds (i.e., a "pre-echo") to a delay of +2.56 microseconds. The combination of echo-canceling hardware and inherent system immunity showed an advantage of about 20 dB to the digital systems. Among the digital systems, AD-HDTV was judged significantly superior for this attribute.

Flutter

Flutter is time-varying multipath. DigiCipher and CCDC exhibited significantly superior tolerance of this impairment.

Impulse noise

The test compares proponent system performance to that of NTSC. All digital systems performed better than NTSC and Narrow-MUSE performed the same as NTSC. DSC-HDTV was significantly better than the other systems.

Discrete frequency interference

CCDC performed best for in-band discrete frequency rejection for the frequencies tested because its worst case (most vulnerable) frequencies tolerated significantly more undesired signal than the other systems at their most vulnerable frequencies.

DSC-HDTV performed best for out of band discrete frequency rejection for the same reason.

Cable transmission

Composite second order

Composite second order (CSO) impairment arises from the distortion characteristics of active elements in a cable television system. System performance in the presence of CSO impairment is a function of the spectral characteristics of the modulation scheme and the receiver front end design.

The DigiCipher and CCDC systems each exhibited resistance to composite second order intermodulation distortion that was significantly greater than that of the other systems.

Composite triple beat

Composite triple beat (CTB) impairment also arises from the distortion characteristics of active elements in a cable television system. Along with random noise, it is one of the primary limiting characteristics in cable system transmission performance. System performance in the presence of CTB impairment is a function of the spectral characteristics of the modulation scheme and the receiver front end design.

The DSC-HDTV and AD-HDTV systems revealed significantly greater immunity to composite triple beat products than did the remaining systems. The system design measures taken to protect the signals from co-channel interference are also effective in providing immunity to composite triple beat.

Phase noise

Phase noise is a function of the stability of oscillators used in the transmission chain to generate or translate the frequency of the transmitted signal. All of the digital systems exhibited substantially greater immunity from phase noise than did the Narrow-MUSE system.

Residual FM

Residual frequency modulation is another form of deviation in oscillators used in frequency conversion equipment. The DigiCipher and CCDC systems tolerated considerably greater residual frequency modulation than did the remaining systems.

Local oscillator pull-in range

Variations in received frequencies are of concern to both broadcasters and cable operators. A consumer receiver must be able to identify and acquire signals that are offset from the nominal frequency assignment.

The DigiCipher, DSC-HDTV, and CCDC systems demonstrated a substantially wider local oscillator pull-in range than the other systems. The DSC-HDTV system range exceeded +/- 100 kHz, the maximum value prescribed in the formal test procedure.

System performance in the presence of phase noise, residual FM and received signals that are offset in frequency, is largely a function of tuner design and implementation and therefore may be expected to improve with a second iteration of prototype equipment delivered for testing.

Channel change

Current television viewers are accustomed to rapid channel change capability, and an ATV service must emulate this feature closely if consumer frustration is to be avoided. Channel change time is a function of two processes: carrier acquisition and bit stream synchronization; and bit stream decompression through recognizable picture display and presentation of audio.

The DigiCipher, DSC-HDTV, and CCDC systems completed a channel change in approximately one second, versus substantially longer times recorded for Narrow-MUSE and for AD-HDTV.

Co-channel interference into ATV

DigiCipher and CCDC were most robust to co-channel interference from ATV. AD-HDTV was best at rejecting co-channel interference from NTSC. (See 2.)

Co-channel interference into NTSC

Narrow-MUSE performed significantly better than the digital systems for ATV-into-NTSC co-channel interference. All digital systems required about the same signal level to cause co-channel interference into NTSC. (See 2.)

Adjacent-channel interference

Narrow-MUSE performed significantly better than the digital systems on lower adjacent-channel ATV-into-NTSC interference by causing the least interference.

Among the digital systems, DSC-HDTV performed best in rejecting ATV-into-ATV and NTSC-into-ATV adjacent-channel interference. DigiCipher and CCDC caused the least upper adjacent-channel ATV-into-NTSC interference. DSC-HDTV, AD-HDTV and CCDC caused the least lower adjacent-channel ATV-into-NTSC interference. (See 2.)

Taboo interference

Narrow-MUSE performed significantly better than the digital systems for ATV taboo interference into NTSC. Among the digital systems, DSC-HDTV had the best all-around ability to reject taboo interference on the nine channels tested; however, the performance of all digital systems was close.

Channel acquisition

The test measured the time required to acquire the signal and display a recognizable picture under a variety of impairment conditions; signal conditions were always above TOV. The performance of DigiCipher, DSC-HDTV, and CCDC was judged superior to the other systems. The three cited systems were able to deliver a recognizable image within about one second under conditions of moderate impairment.

Failure and recovery appearance

The test simulated signal fading in fringe areas for digital systems. Signal strength was reduced below threshold level and then increased above threshold; the resulting image behavior was observed. In general, all systems "froze" the image as the signal fell below threshold. Typically, the image became "blocky" and dissolved into other characteristic artifacts. Recovery was most rapid for AD-HDTV (much less than one second). DigiCipher recovered with characteristic panel wiping, lasting about 1/3 second. CCDC recovery generally consumed about 1/2 second but could last longer than one second. DSC-HDTV required the longest recovery period, generally 2-5 seconds. The speed and subjective appearance of AD-HDTV's recovery were judged significantly superior to the other systems.

Power

Peak-to-average power ratio

The ratios of peak-to-average power for the digital modulation schemes are listed in 9.

The peak-to-average power ratios of DigiCipher and CCDC were judged significantly superior among the digital systems.

Average ERP

The maximum average ERP for each digital system required to achieve ATV noise limited coverage comparable to NTSC Grade B coverage is listed below:

	DigiCipher	DSC-HDTV	AD-HDTV	CCDC
99% of time	4.8 dB	6.3 dB	<6 dB	<5.2 dB
99.9% of time	<6 dB	7.6 dB	<6.7 dB	<6.2 dB

Figure 9. Ratios of peak-to-average power for the digital modulation schemes.

DigiCipher	38.23 dBk
DSC-HDTV	38.25 dBk
AD-HDTV	40.42 dBk
CCDC	37.66 dBk

It is noted that AD-HDTV required significantly more average ERP than the other systems.

Multiple impairments

The broadcast portion of this test determined the point of acquisition (POA) — which needed only to be a "recognizable" image, not a "watchable" one — under different conditions of random noise and co-channel impairments. The test results show that DSC-HDTV could acquire signal under the worst combination of these impairments, with AD-HDTV very close in performance. DigiCipher and CCDC required a significantly more favorable combination of conditions for signal acquisition.

The cable portion of this test measured TOV under different combinations of random noise and composite triple beat. The test results show that DigiCipher, DSC-HDTV, and AD-HDTV exhibited better performance than CCDC. All digital ATV systems, however, are expected to operate with adequate margins to noise and CTB on existing cable systems designed for carriage of NTSC signals for the nominal ATV power levels tested.

Threshold characteristics

Narrow-MUSE, as expected from its analog signal format, exhibited gradual degradation of image quality with decreasing C/N. All of the digital systems had sharp thresholds, with image quality degrading from an unimpaired picture (TOV) to an unusable picture (POU) over less than a 2 dB change in C/N. Based on certification documents, this performance was expected for DigiCipher and CCDC. The claimed gradual thresholds of DSC-HDTV and AD-HDTV were judged to have utility only for short, temporary, and infrequent signal fading.

Audio threshold performance was also characterized. For all of the digital systems, there was no evidence that audio failed before the accompanying video.

Transmission robustness findings

1. A variety of different modulation and signal formats was evaluated. In general, the analysis conducted by the Advisory Committee clearly indicates that an all-digital approach is important in satisfying the selection criteria. Of the four digital transmission systems tested, the Special Panel was unable to recommend a single system.
2. Among the digital systems, both sharp and claimed gradual thresholds were tested. No video performance advantages were found in the forms of gradual signal degradation tested.
3. It is desirable to maintain audio service during momentary disruptions in the picture.
4. The four digital systems tested provided adequate levels of operating margin with respect to composite second and third order impairments.
5. Special attention will need to be paid to the final design of tuners in ATV receivers to achieve immunity to typical levels of phase noise and residual frequency modulation. Although the digital systems performed better, as a class, than the Narrow-MUSE system, none performed adequately for typical levels of these impairments in conventional cable equipment.
6. Careful tuner design is required to assure the acquisition of signals that are offset from their nominal assigned frequencies. As tested, three of the digital systems achieved acceptable performance.
7. While three of the digital ATV systems tested exhibited channel change performance close to that required, none demonstrated optimal performance. Current television viewers expect channel change to be completed nearly instantaneously. Minimizing consumer dissatisfaction with ATV service will require similar performance, certainly well below one second.
8. While the subjective quality tests of cable distribution indicated no degradation, the transmission conditions simulated were not representative of a wide range of real-world cable television plant. Only the field tests will provide final data regarding actual cable transmission performance.
9. DigiCipher's ability to reject an undesired adjacent or second adjacent signal was significantly worse

than the other systems. The proponent has identified an improvement in the system's IF filter which should be verified.

10. Taboo and adjacent-channel performance are dependent on tuner and IF selectivity. Important design information can be obtained from the systems' blackbox tuner/IF characteristics. The proponents should submit both the tuner characteristics of the test hardware and their suggestions for minimum tuner performance.
11. Improvements to the transmission system suggested by the digital proponents include better error correction and concealment, improved receiver RF filters, and techniques to reduce transmitter peak power. Each of these improvement categories addresses specific shortcomings cited in the test results.

Scope of services and features, extensibility, and interoperability considerations

Scope of services and features

Scope of Services and Features considered the need of an ATV system to support features and capabilities beyond those explicit in other selection criteria. The following were considered as a basis of differentiating among the proponent systems: initial use of ancillary data, audio, data, text, captioning, encryption, addressing, low cost receiver, and VCR capability.

All systems provided for data transmission. With respect to data, the AD-HDTV system was judged superior because it used a packetized data structure with headers and descriptors that has been determined, in general, to be important to providing system flexibility. With respect to addressing, the AD-HDTV system was considered better than the other digital systems due to its ability to reassign its entire 18.5 Mbits/sec to addressing keys.

Low cost receiver and VCR capability did not expose substantive differences among the five systems.

The remaining five features did not show significant differences among the four digital systems, but overall the digital systems ranked better than the Narrow-MUSE system (though the difference was small).

Extensibility

Extensibility considered the ability of a transmission system to incorporate extended functions and future technology advances. The following were considered as a basis of differentiating among the proponent systems; extensibility to: no visible artifacts, studio-quality data rate, higher resolution, VHDTV, UHDTV, and provision for future compression enhancements.

It was concluded that the use of a packetized data structure with universal headers and descriptors provides important flexibility in meeting this selection criteria. For example, if a higher data rate channel is used to distribute programming to television stations, additional packets (with appropriate headers and descriptors) could provide higher quality images for post-production processing.

Overall, the digital systems ranked better than the Narrow-MUSE system; however, there were no significant differences among the digital systems.

Interoperability considerations

Interoperability considered delivery over alternative media (cable, satellite, packet networks), transcoding (with NTSC, film, and format conversion to other video standards), integration with computers and digital technology, interactive systems, the use of headers/descriptors, and scalability.

Progressive scan and square pixels are important for computer and other image applications. For interoperability with computers, DSC-HDTV and CCDC ranked better than the other systems.

Only AD-HDTV had its final proposal for a packetized data structure and headers and descriptors fully implemented at the time the system was tested by ATTC, and it received the highest rating on these characteristics. All digital system proponents now recognize the importance of a packetized data structure combined with headers and descriptors as a critical enabling concept for ATV flexibility. As cited in the comparative analysis, examples are SMPTE Header/Descriptor, flexible channel reallocation, compatibility with telecommunications and computer networks.

With respect to format conversion, Narrow-Muse does not require conversion to 1125/60, and AD-HDTV's use of MPEG-1 provides the possibility of interoperability with MPEG applications.

The four digital systems were judged better than Narrow-Muse for interoperability with digital technology, NTSC, film, still images, and interactive systems. Note that latency and acquisition time are important for interactive systems, but have not been completely determined.

All five systems were judged suitably interoperable with satellite and cable.

Findings for scope of services and features, extensibility, and interoperability considerations

1. The analysis conducted by the Advisory Committee

clearly indicates that an all-digital approach is important in satisfying these selection criteria.

2. All four digital proponents have implemented, or now commit to implement, both a flexible packetized data transport structure and universal headers/descriptors. Their design and implementation need to be verified consistent with relevant industry standards and practices and with respect to the ATV selection criteria.
3. DSC-HDTV and CCDC are progressively scanned at 60 Hz and have square pixels. AD-HDTV provides progressive-scan transmission at 30 Hz and claims a potential migration path to square pixels. DigiCipher claims a possible option for progressive scan transmission at 30 Hz. A transmission format based on progressive scan and square pixel is beneficial to creating synergy between terrestrial ATV and national public information initiatives, services, and applications. The ATV design, implementation, and migration paths need to be fully documented by the proponents and analyzed for suitability in addressing these needs.
4. None of the systems achieved the desirable degree of scalability at the transmission data stream that would permit trade-offs in "bandwidth on demand" network environments.

8. Recent developments

On May 24, 1993 the four digital system proponents announced that they had formed a "Grand Alliance" which would make a single system proposal to the Advisory Committee combining the best features of each of the individual proposals. The proposed system contained two scanning formats. The first proposed format has 720 active lines, 1280 pels per active line, and 60 frames per second scanned progressively. The second proposed format uses interlace scanning with 960 active lines and 1408 or 1728 pels per active line. The proposed ultimate target is 960 active lines with 1728 pels per active line scanned progressively at 60 frames per second. The proposed compression algorithm is similar to MPEG-2 with enhancements from each of the original individual systems. A single audio system was not proposed, but will be selected from among the original individual systems after performing a comparative test. The proposed transport mechanism is packetized and similar to MPEG-2. A single modulation technique was not proposed, but will be selected from among the original individual systems after performing a comparative test.

The Advisory Committee's Technical Subgroup will examine the Grand Alliance proposal. At the request of the ATSC[10], the Technical Subgroup has suggested that the 960 active line format should be replaced with a 1080 active line format containing 1440 or 1920 pels per active line. The Technical Subgroup has suggested also that the compression algorithm should be compatible with MPEG-2. Analysis of the proposal and suggested changes will take place during the summer and autumn of 1993. Full specification of the system is expected before the end of 1993. Laboratory and field tests are expected to occur during the summer of 1994 and adoption of the system by the FCC could happen by the end of 1994. This will make it possible for the United States public to view the 1996 Atlanta Olympics in HDTV by tuning in a local terrestrial broadcasting station.

1. In this paper, the term ATV includes HDTV. The FCC has defined ATV to include the range of advanced television features ranging from improvements to the current NTSC system to HDTV. Note that only HDTV systems are under consideration by the FCC at this time.

2. Virtually all of this paper was extracted from the "ATV System Recommendation" report, usually quoting directly from the report; as such, it represents the work of a large number of dedicated people. The author of this paper served as the chairman of the working party of the Advisory Committee that wrote the first draft of the report and as the chairman of the "Special Panel" which completed the report. The full report is available in the 1993 NAB HDTV World Conference Proceedings, pages 237 - 493, and in the IEEE Transactions on Broadcasting, March 1993, Volume 39, Number 1, pages 2 - 245.

3. The Advisory Committee on Advanced Television Service is chaired by Richard E. Wiley. Other members of the Advisory Committee at the time of the adoption of the "ATV System Recommendation" report were Frank Biondi, Joel Chaseman, Bruce Christensen, Joseph Collins, William Connolly, Martin Davis, James Dowdle, Craig I. Fields, Stanley S. Hubbard, Donald F. Johnstone, James Kennedy, James C. McKinney, Rupert Murdock, Thomas S. Murphy, Jerry K. Pearlman, F. Jack Pluckhan, Ward Quaal, Richard D. Roberts, Burton Staniar, Laurence Tisch, Robert Wright, and subcommittee chairs Joseph Flaherty, Irwin Dorros, and James Tietjen. *Ex officio* members were one representative each from the State Department and NTIA, John Abel, Wendell Bailey, Henry L. Baumann, Tyrone Brown, Brenda Fox, George Vradenburg III, Margita White, Joseph Donahue, Robert Graves, Keiichi Kubota, Jae S. Lim, and Donald Rumsfeld.

4. The Special Panel was chaired by Dr. Robert Hopkins. The Vice-Chair was Alex D. Felker. Other members of the Special Panel were Wendell Bailey, Birney D. Dayton, Irwin Dorros, Richard Ducey, Joseph Flaherty, James Gaspar, Branko J. Gerovac, Reggie Gilliam, George Hanover, Dale

Hatfield, Edward D. Horowitz, Charles Jackson, Bronwen Jones, Renville H. McMann Jr., Robert Niles, Mark Richer, Robert Sanderson, Rupert Stow, Richard J. Stumpf, Craig Tanner, Victor Tawil, Laurence J. Thorpe, and George Vradenburg III. Ex officio participants were the Chairman of the Advisory Committee (Richard E. Wiley), FCC Mass Media Bureau (Roy Stewart), FCC Office of Engineering and Technology (Thomas Stanley), NTIA (Tom Sugrue), Department of State (Richard Beaird), Canadian Liaison (Kenneth Davies), Mexican Liaison (Victor Rojas), ATTC (Peter Fannon), CableLabs (Brian James), ATEL (Paul Hearty), Field Test Technical Oversight Committee (Howard Miller), System-Specific Task Force (John Henderson), Narrow-MUSE proponent (Keiichi Kubota), DigiCipher proponent (Robert Rast), DSC-HDTV proponent (Wayne Luplow), AD-HDTV proponent (Glenn Reitmeier), and CCDC proponent (Jae Lim).

5. The data base for the reference NTSC analysis, and for the ATV analyses, is as of August 1, 1992. The need to maintain comparability for the five ATV systems studied requires that the same data base be retained throughout the analysis process. Although data base changes occur with time, those changes are small.

6. In Puerto Rico, the large number of television stations assigned within the limited area of the island precludes the development of a plan providing 100% accommodation by the methodology employed herein. As a result, those stations are not included in the analysis. The comparative analysis attempted to protect all existing noncommercial vacant allotments; however, it did not attempt to assign them an ATV channel.

7. The same subjective tests showed that, for NTSC stations using the worst permissible offset, a 40-dB co-channel ratio corresponded to a CCIR impairment rating of 3, and that 28 dB corresponded to a rating of approximately 2. Neither the FCC's TV station data base nor the data base used in these calculations show which existing NTSC stations are actually employing precise offset. Consequently, the NTSC baseline interference-limited service area calculations may overstate the actual NTSC service areas by some unknown amount.

8. f(x,y) is a notation representing field strength exceeded at x percent of locations y percent of the time.

9. Perceptual coding techniques take advantage of specific psychoacoustic properties and deliberately seek to create material that matches the source subjectively rather than objectively.

10. The United States Advanced Television Systems Committee (ATSC) was formed by the Electronic Industries Association, Institute of Electrical and Electronics Engineers, National Association of Broadcasters, National Cable Television Association, and Society of Motion Picture and Television Engineers to coordinate the development of voluntary national technical standards for advanced television systems. ATSC's fifty plus members are manufacturers of professional and consumer equipment, broadcasters, cable operators, satellite operators, motion picture companies, professional societies, and universities.