The U.S. HDTV standard

THE GRAND ALLIANCE

This standard for digital high-definition television will be submitted to the Federal Communications Commission this summer for its approval.

The fundamentals of television have been reinvented for the digital age. Home delivery of a digitally clean, panoramic, high-definition image, accompanied by digital surround sound audio, could be just around the corner. And it would be broadcast terrestrially, as well as by cable and satellite.

Such a vision moved the Federal Communications Commission (FCC) in 1987 to spearhead a competitive testing and standardization process in the U.S. marketplace. Years of developing rival high-definition television (HDTV) system prototypes followed, but in 1993, the key U.S. contenders came together in a Grand Alliance aimed at developing a U.S. standard for terrestrially broadcast HDTV. This spring, prototype hardware is being tested at the Advanced Television Test Center in Alexandria, Va. This summer, the proposed standard is to be submitted for final certification to the FCC.

Based as it is on the MPEG-2 video compression and transport protocol, multiple transmission formats, Dolby AC-3 digital audio, and vestigial sideband digital modulation, the HDTV system will supply the home with superb images and spectacular sound while also, as part of the National Information Infrastructure (NII), relaying digital data. In society at large, the digital technology involved is expected to create new business activities and stimulate key industries, such as semiconductors, computers, communications, and displays, giving the United States a chance at once more dominating consumer electronics. The impact of HDTV technology on the consumer and the national economy should be felt for decades.

An HDTV system employing multiple transmission formats, digital compression, packetization, and modulation techniques is a marked advance over current world television standards such as NTSC, PAL, or Secam (in full, National Television System Committee, phase alternation line, and Séquentiel Couleur Avec Mémoire).

These analog systems deliver noisier and lower-resolution video and audio, with less flexibility and more processing artifacts. Their success has been immense, but the technology they use is now more than 40 years old. In those decades, major advances have occurred in such key enabling technologies as signal processing, telecommunications, digital compression and transmission, and very large-scale integration. In the past, for example, the idea of giving an ordinary television receiver enough memory to store an entire frame of image data was unthinkable. Today it is unthinkable not to utilize digital memory for video compression technology.

Under the proposed standard, homes will receive an HDTV picture composed of more than two million picture elements (pixels), approximately six times the spatial resolution of present NTSC images. Progressive scanning, one of the format attributes supported in the proposed system, will provide a temporal resolution of 60 full frames per second, twice the 29.97 frames per second of standard NTSC images. The motion seen will be smooth enough for sports fans and computer graphics experts, and details will be fine enough to be viewed up close even on very large television screens. The picture will be presented in a panoramic horizontal-to-vertical aspect ratio of 16:9, as in the movies—a big improvement on the 4:3 aspect ratio of today’s home receiver.

For viewers, perhaps the biggest bonus will be the absence of all the NTSC artifacts. Since the
HDTV images will be digitally clean, there will be no ghosts or beats from unwanted modulation products in the transmission channel; no snow on weak channels, as the viewer will receive only clear images within the broadcast coverage area, no chrominance artifacts, which show up as false and artificial colors on detailed patterns; and no color tint errors. The signal will be either excellent or absent.

As for what is heard, the digital surround sound system will be on a par with compact discs for quality.

Within each 6-MHz channel bandwidth, the proposed initiative, since it can carry not only HDTV data, but such digital data as electronic newspapers or stock prices to homes. The ability to deliver high-resolution video and audio in a cost-effective manner is also expected to influence video communications applications, including picture phones, video conferencing, and multimedia.

**HDTV'S HISTORY**

HDTV research and development began in Japan back in 1968. NHK, the government-sponsored television broadcaster, joined forces with Japanese electronics manufacturers and the government there in a massive project that absorbed well over US $1 billion. The resulting analog system, called multiple sub-Nyquist encoding (MUSE), utilizes digital signal compression, analog transmission, and satellite delivery direct to consumers.

In the United States, the allocation of the television broadcast spectrum came under attack in the mid-1980s by mobile radio interests that wanted to have part of the upper UHF band. The FCC agreed to reallocate some of the unused spectrum, but broadcasters counter-attacked by insisting that the spectrum was needed for advanced television services.

To lend substance to the claim, demonstrations of MUSE-encoded TV were conducted in Washington, D.C., in early 1987. A modified UHF broadcast transmitter sent the signal over the air from a suburb to the FCC, the National Association of Broadcasters, and the U.S. Capitol. The event was politically successful, although technical challenges remained: the MUSE signal occupied two 6-MHz NTSC channels, was quite susceptible to ghosting, and contained motion artifacts.

MUSE and other HDTV proposals had to use satellite delivery because of their large bandwidth requirements and were not directly applicable to broadcast television. In recognition of this fact, 58 U.S. broadcast organizations in August, 1987, petitioned the FCC to inquire into the setting of terrestrial broadcast standards for advanced television. So in September, the agency created the Advisory Committee on Advanced Television Service. Richard E. Wiley, a former FCC chairman, has chaired this committee for seven years, under four FCC chairmen.

Many people thought that the new broadcast standard would be either enhanced-definition television (EDTV) or HDTV, then some derivative of MUSE. They were wrong. By the end of 1988, the FCC had received 23 advanced television proposals.

In the same year, broadcasters and the Electronic Industries Association (EIA) established the Advanced
Television Test Center (ATTC) in Alexandria, Va., to test all proposed HDTV systems. CableLabs, Boulder, Colo., an R&D group supported by the cable television industry, agreed to provide the ATTC with cable-related testing. The FCC advisory committee thereupon contracted with the two organizations to test the dozens of proposals. Subjective evaluations of picture quality and the effects on it of transmission impairments were to be conducted in Ottawa at the Advanced Television Evaluation Laboratory (ATEL), established for the purpose by the Canadian governmental Communications Research Centre.

**Key FCC decisions**

In March 1990, the FCC announced a number of key decisions. First, it decided in favor of simultaneous broadcast rather than the augmentation of NTSC signals. The latter process combines the NTSC signal with an augmentation signal in a second channel to create HDTV, and its signals are backwardly compatible with standard NTSC signals. In the simulcast approach, the HDTV signal is fully self-contained and is transmitted in a single television channel. It does not depend on the NTSC signal nor is it compatible with normal NTSC reception.

Even so, the FCC realized that a simulcast approach would allow a transition period during which NTSC and HDTV could both be on the air; thereafter, the NTSC spectrum could be recaptured and reassigned as that kind of broadcasting was phased out. (Zenith Electronics Corp., Glenview, Ill., and the Massachusetts Institute of Technology had championed the use of a simulcast approach.)

Second, the agency announced its preference for HDTV over the less demanding EDTV, saying that it would rule first of all on HDTV. Delving a view widely held in the United States, Europe, and Japan, the agency changed the tenders to deliver HDTV in a single 6-MHz broadcast channel.

Each developer of an advanced television system was required to submit an application for ATTC testing and to make an initial payment by May 31, 1990. Then, just ahead of the payment deadline, Chicago's General Instrument Corp. (GI) trumped the field by filing the first proposal for all-digital HDTV. The technology was widely held to be many years in the future, but GI had learned how to apply frequency compression to fit multiple NTSC channels into a single satellite transponder channel.

Though there were skeptics, the news galvanized the competition. By year-end, another contender announced that it was switching over to an all-digital HDTV system: the Advanced Television Research Consortium (ATRC), which consisted of the National Broadcasting Co. and Philips Electronics North America Corp., both of New York City; the David Samoff Research Center, Princeton, N.J., and Thomson Consumer Electronics Inc., Indianapolis, Ind.; Zenith, too, teamed up with AT&T to create an all-digital system. Finally, in January 1991, MIT teamed with GI and made the MIT system all-digital.

Along with four all-digital HDTV systems had now been proposed for testing at the two test organizations. There were two other proposals as well. The NHK Narrow MUSE system, with analog transmission, was a 6-MHz bandwidth technology slimmed down from the original 30-MHz MUSE. An NTSC-compatible EDTV proposal put forward by the Advanced Television Research Consortium was later withdrawn.

All six systems were tested successfully at the ATTC and ATEL during 1991-92. In response to an FCC advisory committee request, and under intense competitive pressure, all remaining contenders expressed a desire to upgrade their digital audio systems from two-channel stereo to five-channel surround sound and to provide flexible packetized transmission like that of the pioneering ATRC system.

The advisory committee then set about picking the winner, convening a special panel for the job in February 1993. The panel decided on all-digital technology, but could not select a clear winner among the four all-digital systems. It recommended further testing and also asked for improvements.

**Enter the Grand Alliance**

The advisory committee not only approved the panel’s recommendation but went a step further. Aware that the competitiors had been discussing a merger, the committee went on record as supporting a Grand Alliance of the all-digital contenders. Accordingly, after months of negotiations, the Digital HDTV Grand Alliance was announced on May 24, 1993, by its seven members: AT&T, GI, MIT, Philips, Samoff, Thomson, and Zenith. Its goal was to utilize the best features of the four earlier systems in a “best of the best” system and HDTV standard.

Most of the rest of 1993 was devoted to system definition. Technical specialist groups of the Grand Alliance resolved details and cooperated with the FCC committee’s expert groups, and in October of 1993, that committee’s Technical Subgroup approved the definition as submitted. Approval of one element, the modulation subsystem, was deferred until early 1994, following a “backoff” competition. The modulation subsystem was then taken to Charlotte, N.C., where extensive field testing clearly established the superiority of digital transmission.

Finally, last year, the Grand Alliance system was constructed. AT&T and GI jointly built the video encoder. Philips constructed the video decoder. Samoff and Thomson cooperated in building the transport subsystem, and Zenith built the modulation subsystem. Dolby Laboratories Inc., of San Francisco, is supplying its AC-3 digital sound system. Following system integration at Samoff, the Grand Alliance prototype HDTV system is to go to the ATTC for laboratory testing, which will again be conducted by ATTC, CableLabs, and ATEL. The full prototype will then be sent to Charlotte for field testing.

The advisory committee will complete its work this year by giving the FCC its recommendation on HDTV standards. The FCC then will issue a Notice of Proposed Rulemaking en route to the Report and Order that will officially set the standard, perhaps before the end of the year.

The FCC will be supported in its standards-setting by the Advanced Television Systems Committee (ATSC), which is writing the HDTV Broadcast Standard specification, and by organizations such as the EIA and the Society of Motion Picture and Television Engineers, which are writing industry voluntary companion standards.

**ISSUES IN HDTV DESIGN**

Designing a simulcast HDTV system for terrestrial broadcasting in the United States must balance a multitude of issues: how to utilize the limited broadcast spectrum efficiently, while delivering high-quality high-definition pictures and audio and ensuring the integrity of existing NTSC broadcasts. A transitional phase will have to be arranged for broadcasters and program providers, and the consumer electronics industry will have to develop new receivers. The HDTV system must be interoperable with other media. Technological hurdles associated with system deployment will require solutions.

In a simulcast approach, a stand-alone HDTV signal is transmitted in a single television channel. Because of the limited availability of new broadcast spectrum, the FCC decided that HDTV broadcasts should occupy no more than the standard 6-MHz allotment for NTSC. Since NTSC broadcast must remain intact, channels currently off limits for broadcasting will have to be used for the new HDTV service.

The taboo channels exist because, for a given broadcast area, the normal television spectrum has channels of 6-MHz bandwidth spaced 6 MHz apart. In two
geographically adjacent broadcast areas, the spectrum occupied in one is empty in its neighbor, and vice versa, as a consequence, television viewers in adjacent service areas are exempt from interference from neighboring broadcasts.

NTSC is made available to the public through a robust analog synchronization and audio signal. Its availability is generally measured over a coverage area by what are called grade contours. The grade B contour for NTSC is defined by an "acceptable" picture performance of better than a 28-dB signal-to-noise ratio in half the locations in the area of broadcast coverage, 95 percent of the time.

In an HDTV broadcast system, the same considerations apply. It should be understood that unlike analog systems, digital broadcast systems work almost perfectly to the edge of the service area but fail rapidly with a sharp increase in bit error-rate, when operating below what is termed the threshold carrier-to-noise ratio.

An HDTV simulcast system for the terrestrial U.S. environment must deal with random noise and co-channel interference. It must also provide coverage comparable to that of NTSC. For a grade B coverage area, co-channel broadcasters (neighboring service areas relying on the same 6-MHz channel) that are the minimum 155 miles apart should deliver acceptable pictures up to a radius of 55.5 miles from the broadcast tower. They should be capable of withstanding high levels of interference from, and produce low levels of interference in, co-channel NTSC broadcasts.

Another key requirement for a U.S. HDTV system is flexibility enough to support a broad scope of services and serve many applications, both current and future. Novel uses of video, audio, and data in new products and services will require interoperability among diverse types of delivery media, as well as among a wide variety of consumer electronics, telecommunications, and computing equipment in the home and office.

Interoperability is needed to make the system easy for consumers to use, to expand the marketplace, and to give the electronics industry an incentive to embrace HDTV technology. Among compressed video formats, in addition, interoperability would encourage synergy between HDTV and other computer and multimedia applications. Adopting the same video and audio compression standards in both the computer and consumer industries will facilitate the direct exchange of compressed video and audio, eliminating the cost and artifacts associated with repeated compression and decompression.

The HDTV system must in addition be flexible enough to operate over cable and broadband optical-fiber networks and with various source and display scanning formats, so that filmed material can be used optimally in tandem with sporting events and typical broadcast material.

**The Five HDTV System Functions**

* The Grand Alliance HDTV system functions are format selection, video coding, audio coding, transport, and transmission [see diagram above]. Not every television application has the same performance requirements—hence the appeal of multiple formats, which permit tradeoffs specific to each family of program material. Digital representation and processing in an HDTV system allow the support of more than one scanning format, while facilitating interoperability among formats and different video services and applications.

The formats chosen for the Grand Alliance HDTV system support a range of program material, using two line structures and several frame rates. The proposed specification includes two main formats variations, with 720 and 1080 active lines per frame. Active lines represent the picture elements that are coded and transmitted; some other lines, in the vertical blanking interval, are not sent. In NTSC, for example, there are about 481 active lines per frame, with 44 lines in vertical intervals (22 in each field), for a total of 525 lines. The new 720-line format uses 1280 active samples per line and the 1080-line format uses 1920. Those choices yield square pixels for all formats, with
Suggested applications of HDTV formats

<table>
<thead>
<tr>
<th>Format</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>720 x 1280 P, at 60 frames per second</td>
<td>Sports, concerts, animation, graphics, up-converted NTSC, commercials</td>
</tr>
<tr>
<td>720 x 1280 P, at 24 or 30 frames per second</td>
<td>Complex film scenes, graphics, animation, possible reduced data rate</td>
</tr>
<tr>
<td>1080 x 1920 P, at 30 frames per second</td>
<td>Scenes shot with an interlaced-scan camera</td>
</tr>
<tr>
<td>1080 x 1920 P, at 24 or 30 frames per second</td>
<td>Films with highest spatial resolution</td>
</tr>
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</table>

* P = progressive scanning, I = interlaced scanning.

A picture aspect ratio of 16 by 9. These formats, plus simple conversions among them, can cope with broadcasting, computer multimedia, computer graphics, industrial imaging, and the like.

For the progressively scanned 720-line format, the frame rate can be 60, 30, or 24 Hz. (Lines are scanned in succession, whereas the interlaced format, like that used for NTSC, scans every other line every other frame.) The 1080-active-line format includes an interlaced version at 60 fields per second, as well as a progressive-scan variation for film modes at 24- and 30-Hz frame rates. (All of the formats are also supported with the NTSC-related frame rates, namely, 59.94 Hz, 23.976 Hz, and 29.97 Hz, on the grounds that the 59.94 Hz frame rate may simplify working with NTSC material during the intervening simulcast period.)

As for compression of a 1080-line progressive-scan format at a 60-Hz frame rate, the Grand Alliance determined that at the present time this approach could not provide adequate HDTV quality if it used available channel capacity—hence the inclusion of a 1080-line interlaced format. Exclusively progressive-scan transmission can be supported as it becomes technically and economically feasible.

The pixel clock rate is 74.25 MHz for the 60.0-Hz frame or field rate and approximately 74.18 MHz for the 59.94-Hz frame or field rate, which is 1000/1001 times the 60.0-Hz rate.

One consequence of a multiple-format capability is the need for transconversion before and after coding. A transconverter at the encoder input converts pictures for coding and transmission in a format other than the source's format. Similarly, a transconverter at the decoder output lets the format of the final display—the one the viewer sees—be different from the received format. It is highly unlikely, for instance, that television receivers will change their display scanning parameters to display different formats; instead, they will convert whatever is received into the format designed into their displays.

The ability to decouple the transmission or coding format from the source format makes for flexibility. For instance, if interlaced video is presented to the system, then the user has the option of deinterlacing, followed by transconversion to a progressive format, typically 1280 active pixels by 720 active lines at 60 frames per second. In addition, the decoder's output must be converted to drive a given display format when the decoder receives multiple formats [see tables on this page].

The display format is independent of the transmission formats, since the display itself is not expected to switch between formats. A decoder will provide frame buffering for all formats, and transconversion will derive the display format. If interlacing continues to be used for transmission, a deinterlacer must be part of every receiver with a progressive display.

To tackle feature films, the Grand Alliance HDTV proposal includes 24- and 30-Hz frame rates, with the corresponding adjustments for NTSC-related frequencies. Consequently the encoder will be designed to encode the reduced frame rate from image sequences that originated at 24 and 30 Hz. For both the 720- and 1080-line formats the encoder will identify and exploit the fewer frame rate if the film-mode material is presented to it at 59.94 Hz or 60.0 Hz.

Once again, the initial set of scanning formats can be extended for higher performance or to satisfy the needs of new applications when those become technically and economically possible. In fact,
a generally agreed upon goal is eventually to include the ability to transmit a coded 1080-line 60.0Hz progressively scanned HDTV video sequence. Such an accomplishment would be the highest-performance picture format for the HDTV system.

The Grand Alliance believes that one way to achieve this aim is by sending enhancement data (over and above the original system’s coded data) that will complement the basic HDTV stream. A new television receiver would decode both of the data sets and combine them to create a full 1080-line progressively scanned image.

Any of the Grand Alliance formats could be enhanced in this way, that is, the enhancement is capable of building on a compressed progressive-scan 1080-line film mode (30 Hz), 720-line video mode (60 Hz), or 1080-line interlaced scan transmission.

The additional capacity required for the enhancement data stream could have any of several sources. They include increasing compression efficiency, obtaining additional channel capacity from an alternative source (such as an extra channel or transport from another transmission medium), or, after NTSC broadcasting comes to an end, increasing signal power and data rate, or re-using NTSC channel capacity for enhancement and other data.

**Compression to fit**

For compression of video signals, the Grand Alliance uses a motion-compensated discrete cosine transform (DCT) algorithm that was employed by all of the contenders in the first round of testing. DCT exploits spatial redundancy, and motion compensation exploits temporal redundancy. DCT was chosen for its good energy-compaction properties, and the many fast algorithms available afford low-cost implementation. In addi-

- The analog-to-digital converter and clock recovery element turn the analog video input into digital signals for red, green, and blue. It also provides a 27.07MHz clock for use in the transport system and the generation of the presentation time stamps.

Programmable gamma correction compensates for the nonlinear transfer function of cathode-ray tubes, while color space conversion to Y, U, and V uses the SMPTE-240M specifications from the Society of Motion Picture and Television Engineers. It also performs horizontal subsampling of the chrominance color-difference signals. The film detect/reorder function detects 24-frame film material, with a look-ahead feature for smooth transition to and from the 24-frame processing mode. It also rearranges the order of frames for the B-frame processing. The panel multiplexer performs vertical subsampling of the chrominance color-difference signals, then splits the data into six panels for panel encoding processors.

- In the panel encoding processor, the coarse-motion estimator calculates motion vectors for each macroblock with one-pixel accuracy over a horizontal range of ±127 pixels for P pictures and ±63 pixels for B pictures and a vertical range of ±31 and ±15 pixels for frame and field vectors, respectively. This estimator also decides field or frame vectors and field or frame discrete cosine transform (DCT) coding on the basis of mean absolute errors. Custom-designed chips provide the wide-motion-estimation ranges with the full search algorithm. Also, the DCT/fine-motion estimator calculates the half-pixel motion vectors on the basis of reconstructed frames, a decision also based on mean absolute errors. Certain other decisions for each macroblock are based on mean square errors. The panel quantization processor quantifies the DCT coefficients using a threshold that figures in the characteristics of human vision. The macroblock layer data is merged with slice, picture, group of pictures, and sequence layers. The compressed data is then buffered, formatted into packets, and supplied to the transport system. The coded data merge function also determines the global quantization level.

- In the video decoder, the packet analyzer sorts out packets and directs video packets to the rate buffer. A sub-analyzer extracts timing and other control information and supplies them to the system and display controller. The compressed video data are supplied to eight decode engines for variable-length decoding, inverse quantization, inverse DCT, and motion compensation. The decoded video passes to the video buffer, which arranges it into video frames. The last function provides the analog video output.
tion, the Grand Alliance system employs source-adaptive coding and other techniques for greater coding efficiency.

MPEG-2 syntax from the Moving Picture Experts Group will be used. For one thing, the MPEG-2 tool kit supports most of the compression algorithms used by the system proponents. For another, it will promote worldwide acceptance of the Grand Alliance system, which conforms to the MPEG-2 main profile implemented at high level.

The video encoder [see top diagram, previous page] has been designed to support both 1080-line interlaced and 720-line progressive formats. It also supports bidirectional-frame (B-frame) prediction, wide-motion-estimation ranges, field and frame motion vectors, and adaptive field and frame DCT coding, as well as forward analysis with localized quantization-level control and automatic film detection for high picture quality.

B-frame prediction improves compression efficiency by predicting the current frame from past and expected frames. The wide motion-estimation ranges—up to ±127 horizontal and ±31 vertical in the prototype hardware but fully compliant with MPEG-2 requirements—are needed for tracking fast motion. The field and frame motion vectors, and the adaptive field/frame DCT coding greatly improve the compression efficiency for the 1080-line interlaced format. The forward analysis with localized quantization-level control further decreases the visibility of the compression artifacts by exploiting the characteristics of the human visual system.

Of course, the video decoder [at bottom in diagram on previous page] has been designed to support all of the features of the encoder.

Packet delivery

The HDTV system owes much of its power and flexibility to the packetized transport technology employed for the broadcast delivery of the multimedia service. The MPEG-2 systems standard, on which the Grand Alliance HDTV system is based, encapsulates the compressed video, audio, and auxiliary data bit-streams in information packets of a fixed length. These packets are well-suited for terrestrial channels, where transmission errors and data loss are likely. Besides packetization, the transport technology provides two other important functions: multiplexing and synchronization of the services that comprise a program.

Overall, the transport technology creates a stream of fixed-length information packets from a variety of elementary bit-streams (such as video, audio, and auxiliary data). Each packet contains only one type of data: video, audio, or ancillary. As there is no fixed mix of packet types, the transport mechanism can dynamically allocate the available channel bandwidth for complete flexibility.

Each transport packet consists of a 4-byte packet header followed by 184 bytes of payload [see diagram on below]. The header includes means for synchronizing view, can be supplied by conditional access, which permits video, audio, and data to be scrambled independently. Information in a packet's header indicates whether its payload has been scrambled.

Sometimes, extra header information is required—for periodic synchronization of audio and video timing, for example, or random entry into the compressed bit-stream, or local program insertion. Then a variable-length field, the adaptation head-

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anticipated may be implemented in the future. It is therefore crucial that the transport architecture be extensible.

In point of fact, new elementary bit-streams could be handled at the transport layer without hardware modifications if new packet identifiers were assigned at the transmitter and were filtered in the bit-stream at the receiver. Backward compatibility would be ensured, since existing decoders would automatically ignore new packet identifiers—possibly an opening for a compatible form of three-dimensional HDTV.

Dolby-based audio

The system the Grand Alliance is proposing does as much for audio quality as for picture quality. Discrete multichannel digital audio is an ideal match for digital high-definition wide-screen pictures. The sound delivered suits everything from the inexpensive monophonic television with a built-in speaker to the home theater presenting cinema-like pictures and sound.

The audio is supplied by Dolby Labs' AC-3 digital audio compression system, which has beguiled cinema-goers since 1991. The AC-3 perceptual coding system encodes discrete multichannel sound (left, center, right, left surround, and right surround, and low-frequency enhancement channels) into a bit-stream at a rate of 384 kbps. The sound is of better quality than the matrix surround-sound of such current media as broadcast television and VHS Hi-Fi.

The AC-3 coding process involves converting audio signals from the time into the frequency domain. The audio spectrum is continuously analyzed, and significant features are encoded with enough bits to achieve an adequate signal-to-noise ratio. Some of the spectral components are less audible, either because of psycho-acoustic masking (where part of the audio spectrum is overshadowed by a signal component that is near in frequency and digital modulation methods, the signal has additional features that enhance it when reception is difficult. The essential VSB technique was chosen on the basis of laboratory tests of competing systems, but desirable features from these rivals—especially any operating unilaterally at the receiver—can be added.

For broadcast, the system uses a signal designated 8-VSB, comprising a four-level AM vestigial sideband signal plus trellis coding that turns its four-level input into eight-level output signals. The basic data transmission spectrum is flat over most of the channel, with a roll-off region at either edge, like a quadrature amplitude-modulated (QAM) spectrum. But unlike QAM, where the suppressed carrier is in the center of the band, VSBs suppressed carrier frequency is at the roll-off of the lower band.

Constant-value data—all 0s, for example, when the transmitter input is disconnected—would ordinarily produce a nonuniform spectrum, increasing the interference existing NTSC stations. For this reason, input data is modified by a known pseudo-random scrambling sequence, which flattens the spectrum on average [see diagram, p. 44]. Because the MPEG-compliant data generated by the Grand Alliance video compression system is segmented into 188-byte packets including a sync byte, data is transmitted in similar segments. Each contains 187 data bytes, 20 Reed-Solomon parity bytes for forward error correction, and one segment sync byte. This last byte replaces the MPEG sync, which can be re-inserted as required at the receiver.

The one-dimensionality of the VSB signal allows the demodulated baseband multi-level signal to be digitized with a single analog-to-digital converter. Digital circuitry handles all later processing.

Over cable, where the signal-to-noise ratio is controlled, a 16-level VSB modulation suffices without trellis coding. The increase in the number of levels does not alter the signal's spectrum, but does double the available data rate vis-à-vis 8-VSB. The special features added to the VSB signal assist the receiver in acquiring and locking onto that input even under the occasionally extreme conditions of terrestrial broadcasting. The idea is to provide a known and stable reference for the various carrier and clock recovery functions. The receiver is then sure to acquire the
signal whenever the data itself is usable.

The principal special feature is the inclusion of a small pilot carrier instead of the totally suppressed carrier usual in QAM. The pilot is placed so that it falls on the Nyquist slope of NTSC receivers, minimizing co-channel interference into existing service. If there are no other channel impairments, this pilot can be acquired down to a signal-to-noise ratio of 0 dB and provides a margin for signal acquisition under severe conditions, such as ghost or co-channel interference.

**Interoperability ranks high**

Getting a diverse collection of television, imaging, and information systems to work together is difficult because of the proliferation of standards in some industries and the lack of them in others. Still, interoperability has been an important design goal for a U.S. HDTV system since 1990, when the competing digital systems were being developed.

A high degree of interoperability in an HDTV system indicates that a balance must be struck among many different and often conflicting considerations related to broadcasting, cable television, and consumer electronics, as well as computing, telecommunications, and the NIH. These systems are not especially interoperable with one another, yet there are good reasons for making them interoperable with HDTV. Although effortless interoperability with all the systems is impossible, it can always be provided with appropriate interfacing/conversion electronics. In that sense, interoperability is a matter of degree.

Three fundamental principles of the Grand Alliance HDTV system provide a basis for interoperability. First, the layered digital system architecture is compatible with the Open System Interconnection (OSI) model of data communications—the reference model for virtually all modern digital systems. Second, the HDTV system fully exploits the flexibility of a digital system by using a header/descriptor approach, rather than a single, rigidly specified data format. Finally, each layer of the system is designed to be interoperable with other systems at corresponding layers, so that many applications are able to make use of various layers of the HDTV architecture.

The picture formats of the Grand Alliance system provide for square pixels, where the vertical and horizontal spatial resolutions are equivalent, and for progressive scan. At the picture layer, the HDTV transmission standard must be easily interoperable with a wide variety of existing pixel formats, including those used in motion picture film, currently available HDTV production equipment, the NTSC television standard, and such computers as PCs and workstations. This goal is extremely demanding, since these widely accepted standards differ in pixel format, scanning approach (interlaced and progressive), and frame rate. Whereas all but the cheapest computer displays use square pixels and progressive scanning, for instance, there is no one industry-wide standard or even a predominant format. Further, no simple technique of converting among text and graphics representations is commonly available.

**NTSC television, on the other hand, uses rectangular pixel resolution and interlaced scanning, but its international standard (CCIR 601) provides a format for 525-line component video of active 483 lines by 720 pixels. Fortunately, the television industry has developed techniques and equipment for converting images from one pixel format and frame rate to another, achieving interoperability among film and the various world television standards. Indeed, such conversions are common in television and film production.**

As noted earlier, the two pixel formats provided by the Grand Alliance HDTV system are active 1920 pixels by 1080 lines and active 1280 pixels by 720 lines. Each has a 16:9 aspect ratio, the square pixels crucial to computer interoperability. It is should be noted that this choice represents a preference for interoperability with computers rather than with the current NTSC television standard. The two Grand Alliance scan formats are deliberately related by a factor of 3.2, so that a simple interpolation filter suffices to convert one into the other. The scan formats have a like 3:2 relationship to the common VGA computer format of active 640 pixels by 480 lines—VGA has a narrower 4:3 aspect ratio—providing simple interoperability with text and graphics in VGA format.

For the sake of flexibility and interoperability with television, film, and computers, the Grand Alliance formats are progressive scan with one exception: the highest combination—active 1920 pixels by 1080 lines at 60.0 Hz—is interlaced, but retains square pixels. Progressive scanning, because of its many advantages and its importance for interoperability with computers, is used in five of the six combinations of scan formats and frame rates. The remaining interlaced format is preferred only for some types of picture material, such as those used for much entertainment television, and in addition is interoperable with existing interlaced sources. Just as conversions can be performed among various scan formats.
formats, an interlaced scan can be convert-
ed to progressive scan by a deinterlacing
filter that "fills in" the missing lines.
Thus, the Grand Alliance HDTV sys-
tem provides for multiple formats and
frame rates, decodable by any Grand
Alliance HDTV receiver, and convertible
to its particular display format. The flexi-
bile resolution/frame rate transmission
approach, by accommodating various
production standards, will enable diverse
industries, program producers, applica-
tion developers, and users to make their
own tradeoffs among resolution, frame
rate, compression, and interlaced artifacts.
In effect, they are free to choose the for-
mat/frame rate combination that provides
the best picture quality for their particular
use. Receiver manufacturers also benefit
from the freedom to produce a wide vari-
ety of products and consumers from the
freedom to choose among them.

The compression approach of the
Grand Alliance HDTV system turns the
raw video and audio samples into a cod-
ed bit-stream—essentially a set of data
and computer instructions, which the re-
ceiver executes to recreate the original
picture and sound. The system accord-
ingly gains attributes that contribute to
its interoperability with the compression
syntax commonly used by computers and
multimedia systems.

The Grand Alliance video compression
syntax is based on the MPEG-2 video
data compression draft international stan-
dard from the International Standards
Organization and MPEG. This relation-
ship will permit HDTV devices to inter-
operate with MPEG-2 and -1 computer
multimedia applications directly at the
compressed bit-stream level. For example,
consumer HDTV VCRs will be able to
produce an output bit-stream that can be
input to a multimedia computer, and it
will also be possible to interface HDTV
receivers with CD ROMs containing full-
motion video. Although appropriate inter-
faces must be specified, this common
compression standard clearly smooths the
way to interoperability. Even the header/
descriptor that specifies the HDTV system's
multiple format and frame rate capabili-
ties is owed to a mechanism that is part of
the MPEG-2 standard.

The transport subsystem, since it de-
defines the basic format of data packets,
can contribute a lot to interoperability.
This packetizing serves many purposes: it
wraps up the data into fixed-size units
suitable for forward error correction en-
coding; it multiplexes the various el-
ements of the program (video, audio, data,
and so forth), it provides time synchro-
nization for those elements, and (through
the use of packet identifiers in the head-
er/descriptor) it ensures flexibility and
extendibility with backward compatibility.

Again, conformity with international
standards, the system uses a fully compati-
ble subset of the MPEG-2 transport system.
The 188-byte packet has a 13-bit packet
identifier with a powerful header/descriptor
that can combine video, audio, and ancillary
data streams into a single program stream.
No predetermined mix of data is required,
and furthermore, the mix may change
dynamically from moment to moment.
This approach allows great flexibility in
the services that can be provided.

While it is desirable to achieve inter-
operability with other packetized com-
munication systems, the current installed
base of data communications networks
falls far short of this ideal. Using Ethernet,
fiber-distributed data interface (FDDI),
and Internet standards, they all have quite
different packet sizes, formats, and proto-
cols, and require interface electronics to
"bridge" networks. In fact, the emerging
asynchronous transport mode (ATM)
standard uses packet sizes, formats, and
protocols that differ from those of any of
the above standards.

The Grand Alliance HDTV system has
emphasized interoperability with ATM by
using a packet size that is easily encap-
суlated within that transport mode. While
the delivery of MPEG-2 applications over
ATM links is likely to be the most usual
interoperability scenario, the opposite
possibility—delivering ATM data over an
MPEG-2 link—is also provided for in the
Grand Alliance system, plus full function-
ality of both the MPEG-2 and the ATM
transport streams. This approach preserves
the full functionality of both methods.

Transmission interoperability is served
by a serial bit-stream and aided at the trans-
mition layer by the nature of digital sys-
tems. Naturally, different modulation tech-
niques are used for physically different
channels (terrestrial simulcast, cable, satel-
lite, and fiber), but demodulation of these
signals into the serial bit-stream is the basis
for transcoding among the modulation
techniques and ensuring interoperability
among physically different delivery media.

HDTV and the NII

By deploying digital HDTV and creat-
ing a new consumer market, the United
States can accelerate the development
( and consumers' acceptance) of improve-
ments to the nation's information infra-
structure. HDTV can be delivered by exis-
ting cable television systems, and put on
the air quickly by broadcasters. It will cre-
ate a mass market for low-cost, high-
solution displays in agile receivers that use
sophisticated digital circuitry to process
and display multiple pixel formats and
frame rates. Adding a more powerful mi-
croprocessor—a simple one is already
there for control function purposes—to
an HDTV set will yield an NII-ready
information appliance at a small cost.

In fact, the best way of introducing ad-
vanced NII applications may well be to
employ entertainment as a catalyst for
getting the necessary capabilities into the
home. Even so, this move will succeed
only if HDTV receivers are affordable.
Furthermore, some consumers will want
NII capabilities and some may not.

In all likelihood, any HDTV receiver—
even one with an interfaced display—will
serve as an adequate NII terminal for a cor-
nucopia of consumer applications. Not all
information infrastructure applications are
directed at the general public, but still,
the acceptance of NII and its growing use
by consumers will probably generate demand
for more advanced HDTV receivers with
ever more capable processors and displays.
In this way, HDTV could be a catalyst to
the NII's further development and the cre-
ation of new NII applications. Conversely,
as the NII advances, consumers will de-
mand ever more sophisticated HDTVs
and other information appliances.

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