Television
by the Bit

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High-definition television is coming. It will display images with about 1000 scan lines on screens that have aspect ratios of 16:9 instead of the current 4:3. Luminance and chrominance will be properly separated for excellent color rendition, and sound will be in stereo at compact-disc quality.

Viewers will thus experience dramatically enhanced viewing, but to secure it, broadcasters will need to transmit far more information per second to the receiver than they do today. To facilitate this goal, engineers in Japan and Europe are concentrating on developing systems that deliver programming directly to homes from high-power satellites, using direct-broadcast-satellite (DBS) delivery requiring reception with very small dish aerials. At the same time, there will be no interruption to regular, existing TV service in the U.S., where 6-MHz, terrestrial (over-the-air systems) prevail, and there are plans for simultaneous broadcasting with higher resolution.

Extensive debate on what HDTV is, and will be, has produced a terminology with some subtle distinctions. Advanced Television (ATV) is the generic designation for all systems superior to the current one. It covers, for example, Improved Definition Television (IDTV), which implies in-set digital processing of current TV signals; and Enhanced Definition Television (EDTV), which uses advanced encoding and compatible transmission to achieve a resolution that is better than the current NTSC system but not as good as full HDTV systems.

There are various distribution and delivery systems for Advanced Television signals. In addition to satellite and terrestrial systems, cable is a popular delivery mechanism, and is somewhat less constrained than terrestrial TV. Optical fibers, with their wide bandwidth, are well suited for fully digital transmission of HDTV. When they arrive, fiber based Broadband Integrated Services Digital Networks (BISDNs) should be capable of handling HDTV. Storage media such as disks and VTR's will also offer HDTV quality.

Although most proposed transmission

Before June 1990, all of the proposed advanced broadcast television systems were analog. But bit by bit, the tables are turning to digital.

techniques for HDTV are analog, several groups are now investigating the feasibility of fully digital HDTV, and these efforts have created worldwide excitement. Digital video will surely be transported by fiber networks, and we have already seen successful experiments in which all-digital video has been transmitted by satellite [6]. Terrestrial all-digital ATV transmission has now been proposed in the U.S., and the technique would work over coaxial cable as well. The difficulty with digital terrestrial transmission, is that efficient modulation has a limited spectrum efficacy, perhaps of the order of three bits/s per Hz. ATV signals, with access to only 6 MHz of available bandwidth, and in need of overhead error correction, would need to be compressed to 15 Mbits/s, down from almost 1 Gbit/s.

Improving the quality of television poses a series of novel technological challenges. Since exceptionally large bandwidth is needed for transmission of HDTV signals in either analog or digital form, products using this technology will require sophisticated, real-time signal-processing and compression techniques. They will also require large amounts of memory and specialized logic

circuitry, all in VLSI. Furthermore, HDTV will help bring about a new generation of computers in the form of multimedia workstations. For these reasons, the market for HDTV is likely to be a driving force for technologies like semiconductors, computers and telecommunications.

Where Nations Stand

Standards organizations have been working hard, but with limited success, to define a single high-definition television (HDTV) standard worldwide. Because the economic stakes are high, nations and alliances of nations have staked out strong positions to influence the standard-making process. One important issue is whether HDTV should be interlaced or progressively scanned. Current TV is interlaced, but Zenith Corp. has proposed progressive ATV for the U.S. system, and Europe is thinking of a progressive production HDTV standard. Each technique has advantages. In progressive scanning, each scanning line follows its predecessor in a sequential fashion, rather than skipping intermediate lines that are filled in by the next field. Progressive scanning is used in computer displays (Fig. 1a). On the other hand, interlaced scanning increases the number of lines without increasing base bandwidth, but interlacing produces various artifacts. The form of interlacing used in current television schemes is 2:1; i.e., two fields per frame, in which one field contains the even lines and the second field contains the odd lines of a frame (Fig. 1b).

The Japanese Broadcasting Corporation, NHK, pioneered HDTV research throughout the 1970s. In collaboration with other Japanese companies, NHK has unveiled a 1125/60/2 system: 1125 lines, 60 fields per second, interlaced at 2 fields per frame. NHK's name for the corresponding family of transmission systems is MUSE, short for Multiple Sub-Nyquist Sampling Encoding. MUSE compresses the bandwidth of the HDTV and digital sound signals.

In 1986, Europe responded to Japan's HDTV initiatives by launching the large-scale Eureka EU-95 Project, which involves more than 30 companies. Eureka's alternative to MUSE uses the 1250/50 format and the corresponding analog transmission scheme is named "high-definition MAC (HD-MAC)," designed for compatibility with the MAC (multiplexed analog component) system. MAC was proposed as a way out of the many European TV standards

for standard quality television, using DBS transmission. The format is interlaced for transmission.

In the United States the situation is still fluid, with standardization efforts focused on conventional terrestrial broadcasting of ATV. Beset with extensive regulations and the reality of multipath distortion and co-channel interference, terrestrial broadcasting is the most technically constrained mechanism for delivering ATV, and thus it is the most challenging. Possible candidates include 1050 interlaced lines or 787 progressive lines, all with the NTSC field rate of 59.94 Hz, which differs from the 60-Hz field rate of the 1125/60 proposed standard. The Federal Communications Commission (FCC) favors simultaneous broadcasting (simulcast) of a signal compatible with today's NTSC-format television receivers on one 6-MHz channel and a noncompatible ATV signal on a second 6-MHz channel. The NTSC channel would eventually be phased out to conserve bandwidth. This approach implies that the ATV signal must be compressed to fit within the currently allocated channel bandwidth of 6 MHz, with the possibility of using taboo channels.

There are several proposed schemes, including the surprise submission in June 1990 of an all-digital approach by General Instrument Corp. [2]. In November 1990, a second all-digital approach was announced by the David Sarnoff Research Center and its sponsoring consortium of NBC, Philips and Thomson. Technical details may be available by the time this article is published. Other companies are considering a shift from analog to digital systems, so more announcements may be forthcoming.

Efforts to define a single HDTV standard worldwide move ahead slowly

Testing of six rival systems will begin in April 1991, and the FCC plans to choose the American Advanced Television standard in 1993. In addition, Sky Cable has announced plans for all-digital satellite television transmission in the U.S.

Signal Processing of HDTV

HDTV will open new opportunities for research and development, not only in display technologies, but also in three-dimensional signal processing of sampled spatio-temporal video signals. Research in HDTV is distinguished from research in traditional

video by the much higher required speeds and the need for compatibility with other video formats having less resolution. Research areas include video coding, standards conversion, picture crispening and other forms of quality enhancement, de-interlacing for IDTV receivers, and exploitation of interframe redundancy via motion estimation (that is, predicting the velocity of the objects in a scene).

HDTV systems must process about 60 million pixels/s in real time, and yield superb quality Therefore, extremely fast hardware incorporating efficient VLSI architectures must be used. This hardware must also be inexpensive, especially for the receiver. Thus, it is desirable to incorporate asymmetric algorithms, in which the complexity of the decoder is less than that of the encoder.

Compatibility and coexistence between HDTV and systems with lower resolution (for example, standard-quality TV) is another important aspect to HDTV research. Thus, the multiresolution element becomes important in HDTV algorithms. A signal decomposition can be used for a parallel transmission of several channels, each of which could have a different priority or protection, if necessary (Fig. 2). In the presence of increasing channel errors, such a system would degrade quality gracefully by shifting to the immediately preceding resolution.

Will HDTV be Digital?

Most existing HDTV production and transmission schemes are analog or mixed analog and digital. It is now widely acknowledged that the best way of improving the quality of

1. Television systems can be implemented with progressive scanning (a), or interlaced scanning (b).
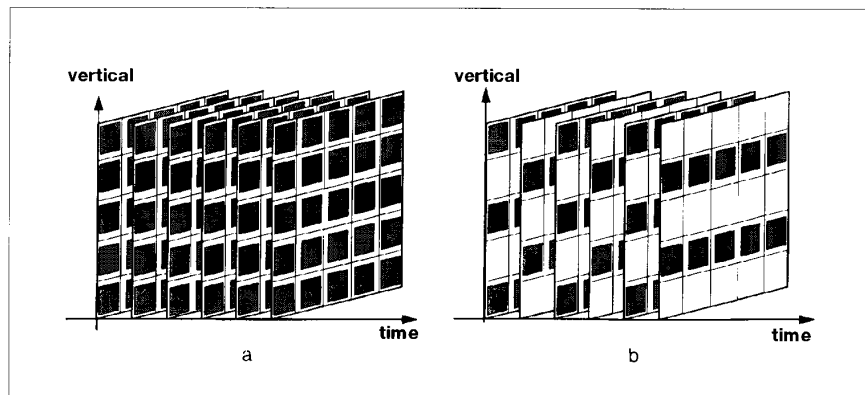
television signals is through digital enhancement. The remaining question is when fully digital transmission will become economically competitive with analog transmission.

Digital HDTV has many advantages, the most obvious of which is flexibility. Once the signal is represented by a sequence of zeros and ones, it can be digitally processed in any way that seems desirable. And, assuming error-free transmission, the signal quality at the receiver will be identical to that at the transmitter. Digital representation is transparent to any video format and requires less transmitter power.

Digital transmission has drawbacks as well. Digital receivers will be more complex, and more expensive, than their analog counterparts. Modulation of digital signals requires more bandwidth than does modulation of analog signals for the same quality, unless very sophisticated compression techniques are used. When designers push the limits of digital video compression, quality artifacts begin to appear for very complex and fast-changing pictures. In fact, maximum compression with constant signal quality requires variable bit-rate (VBR) transmission, but VBR coders can be used only in digital fiber-based packet-switched telecommunication networks. When a constant rate is required, the signal quality, as determined by the coder, will be affected.

System robustness is essential so that bit misinterpretations will not produce catastrophic effects. Error-correction methods can help, but one of the main concerns for all-digital terrestrial TV is that the signal can be transmitted up to the distance in which the bits start being misinterpreted by the receiver as a result of complicated terrestrial channel distortion. However, a proper combination of source and channel coding can achieve graceful degradation at higher distances. For example, hierarchical coding schemes are useful for this purpose because a number of digital transmission channels can be used, each with a priority assignment capable of handling a certain bit error rate. Thus, a transmission error will merely result in a lower resolution signal (Fig. 2). Generalization of this approach to interlaced video is possible but nontrivial, because the sampling structure of standard interlaced TV is not a subset of that for interlaced HDTV.

There are currently efforts to investigate
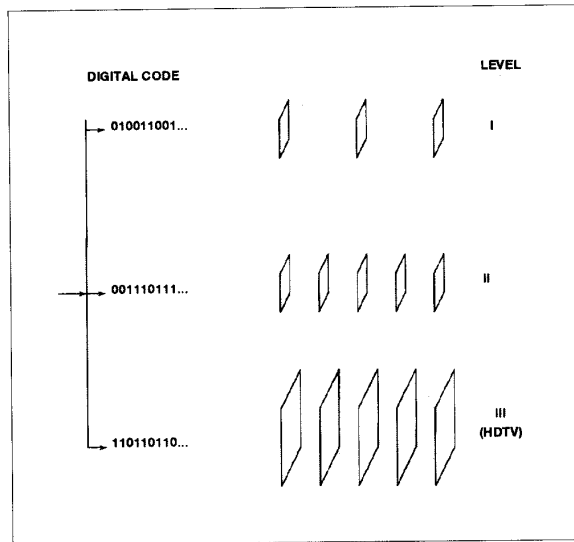
2. Hierarchical transmission is robust and compatible with signals at a variety of resolutions.

fully digital HDTV communication schemes connecting multimedia workstations with high resolution displays, for handling full motion video. For this, it is important to come up with an optimum representation for motion video in computers, considering the trade-offs with respect to processing, architectures, bus and other communication bandwidth, and storage.

The net bit-rate generated by uncompressed HDTV is approximately 1 Gbit/s. It is believed that digital "contribution quality" HDTV. i.e., program material sent from one studio to another, should be in the 200-300 Mbits/s range to permit further editing. On the other hand, "distribution-quality" HDTV, i.e., program material sent to the home, should be in the range of 45-100 Mbits/s. However, many specialists believe that these bit rates can be greatly reduced by using sophisticated compression methods.

Video Compression
The key to reducing the bit rates is signal compression, which depends on sending nothing that is not visible to the human eye and on exploiting the inherent redundancy of the video signal. Digital video coding is done in various ways [5]. The tradeoffs involved include the compression ratio, the quality of the coded signal, and the complexity of implementation, especially for the receiver.

Motion compensation is an important element of high compression. Video scenes typically contain repeated frames of objects

that are essentially unchanged from frame to frame, except for some displacement due to their motion. Motion-related coding operations can improve the performance of video compression. But motion estimation is beneficial only as long as it is accurate, otherwise it may create severe quality problems. To minimize receiver complexity, motion vectors are typically evaluated at the encoder site from the original signal, and then sent as side information to the decoder.

Two widely used digital video compression techniques are predictive coding and transform coding. Predictive schemes compress each pixel by quantizing the difference between a predicted value (based on its coded history) from its actual value. Transform coding, particularly using the Discrete Cosine Transform (DCT), has been established as one of the most powerful approaches. Images are first separated into square blocks of typical size 8x8. Each of the blocks is DCT transformed, resulting in another 8x8 block, whose coefficients are then quantized and coded. Most of the quantized DCT coefficients end up having zero value, resulting in high compression. Applying inverse DCT on the quantized DCT coefficients recovers an approximate version of the original block.

Temporal redundancy is typically exploited by using motion compensation to predict each image frame, and then compressing the difference between the predicted and actual frame using DCT

coding. Such a scheme is called hybrid motion compensated DCT coding (Fig. 3).

As mentioned above, compatibility with other standards, using signals at various spatio-temporal resolutions suggests the use of multiresolution coding. Subband and pyramidal coding techniques are hierarchical in nature. In a typical subband coding scheme, the input signal is sliced into frequency bands that are coded separately, using any compression scheme. Pyramid methods derive a low resolution version of the original signal, from which an approximation of a higher resolution signal is interpolated. The difference between the two is computed and sent together with the low resolution version. This process is iterated to include various stages of downsampling and interpolation, and is well suited to the technique outlined in Figure 2.

There are intensive efforts for standardization of video coding algorithms at various bit rates. The Moving Pictures Expert Group (MPEG) is considering standardization of standard video coding for digital storage media, at about 1 Mbit/s [4]. A second phase (MPEG-2) has been initiated to deal with coding up to 10 Mbits/s. MPEG is based on a multimode hybrid predictive/interpolative motion compensated DCT coding scheme, which is highly asymmetric to minimize receiver complexity. The signal is coded after the even fields are dropped

Digital enhancement offers the best way of improving the quality of TV signals

(i.e., half the fields in Fig. 1b), and the result is a progressive sequence. If the MPEG-2 effort yields excellent quality, it could be used for high-compression HDTV coding as well. One possible hierarchial approach is to

code the even fields using the already coded odd fields.

Implementation Issues
With all the advantages digital television has to offer, an inescapable problem is its increased implementation complexity. For a sobering perspective, real-time digital speech processing could be performed in the 1960s, and most of the conceptual problems were solved then. Real-time digital video processing, however, appeared only in the 1980s, mainly because the required sampling rates are more than three orders of magnitude higherfor standard NTSC television compared with those of speech. In addition, extremely large amounts of digital storage are needed, which are only now becoming available at reasonable cost.

Digital HDTV poses a challenge to the semiconductor industry to provide very fast and inexpensive integrated circuits. Submicron CMOS is the technology of choice for scale of integration and low-power dissipation. Systolic custom-designed architectures are now operating at speeds in the hundreds of megahertz, and are approaching 1 GHz. For exceptionally high speeds, GaAs technology is promising, especially if cost is brought down by increased circuit density.

The technology for realizing digital processing of regular digital video such as CCIR-601 (which has a raw bit-rate of 216

3. Hybrid motion-compensated DCT video coding is an important contributor to high compression transmission of television signals
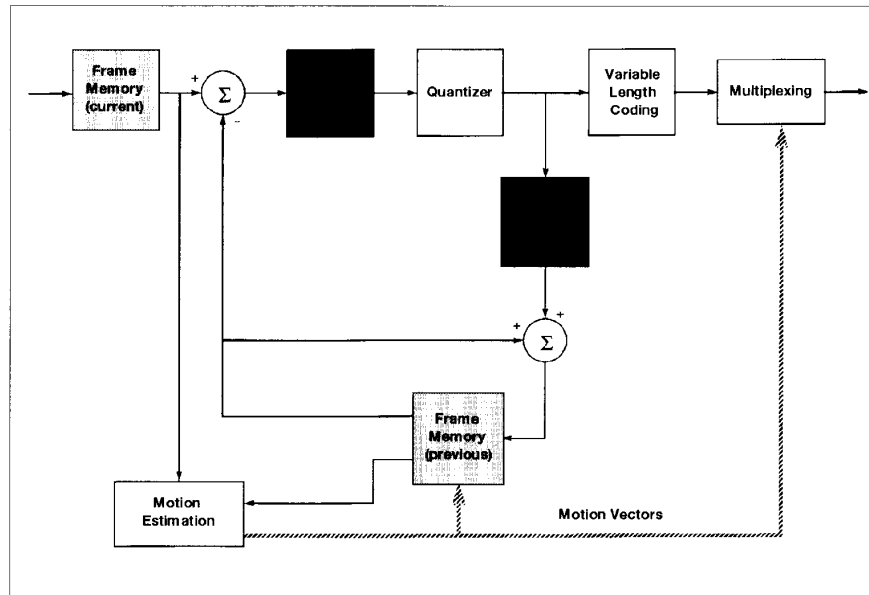
Mbits/s) is available, although not widespread. But the step toward higher-resolution standards poses new challenges in terms of complexity. In most of the proposed HDTV formats, the pixel rate is approximately 60 million pixels per second. Assuming one byte of luminance and one byte of chrominance per pixel, the corresponding data rate is 1 Gbit/s; a rate that must be handled by a digital coder.

Then, there is computational complexity. Two key computations that will probably be part of any advanced digital coder are motion estimation and computation of discrete cosine transforms (DCTs) for image compression. A typical motion estimation algorithm will calculate the displacement vector that best matches a sub-block of the current frame to the next frame. Since large displacements are unlikely, the search region is limited to several pixels around the central point of the block. Still, the hardware would have to perform about 50 billion operations per second!

This problem has motivated the design of custom VLSI chips for motion estimation. Usually, full search is implemented because of its regular structure, and the algorithm is systolizable. This means that the computations can be mapped onto a regular VLSI structure that uses only local communication and exchanges data in a synchronous fashion. This is an important feature because it means that larger problems can be solved with the same architecture by simply extending the systolic array. Current technology permits us to build real-time motion-estimation chips for standard television rates, so HDTV rates should be realistic fairly soon.

Another computation-intensive process in video coders is the calculation of the two-dimensional DCT. Traditionally, this requires N^2 multiplications per pixel for an NxN block of pixels (N is typically 8 or 16). A separable matrix-vector product brings this down to 2N. A number of algorithms have been developed for fast DCT calculation that brings the number down to Log N. Several special-purpose chips have been designed for DCT computation, including matrix-vector multipliers, specialized microprogrammed ALUs, and straight mappings of fast algorithms into silicon. The current chips match regular television rates, and HDTV is within reach, either by parallel use of the current chips or with designs using better technologies.

The advent of very-high-performance

Digital HDTV poses a challenge to the semiconductor industry for fast, inexpensive ICs

RISC (Reduced Instruction Set Computer) chips is expected to reduce the need for specialized hardware designs. The emphasis is likely to be on parallelization of computations so that standard programmable chips can be used. As an example, DCT computation on separate blocks can be easily evaluated on separate processors, and the same holds for motion estimation if the data is adequately duplicated.

Things to Come
Digital video has surfaced, is expanding, and may eventually encompass all delivery mechanisms. Some experts have already suggested that the Japanese and European satellite HDTV transmission systems based on MUSE and HD-MAC, which are mainly analog based, will eventually be abandonded due to "leapfrogging" to an all-digital satellite HDTV technology. The feasibility of all-digital terrestrial transmission is un-

dergoing intense investigation in the U.S. Whether these efforts prove fruitful or not, it is clear that digital video will be transported at various resolutions and various bit rates over various channels connecting computers and television receivers.

What is needed, in addition to advances in display technology, is an international effort for a unified treatment of digital video, including HDTV, so that as many systems as possible can "talk" to each other. This is a difficult task, even in the case of HDTV/Standard TV compatibility. There is a price in performance to be paid for compatibility.

Powerful signal processing techniques are the keys to solving the problems that will undoubtedly arise [1,3]. Efficient conversion schemes between standards will help, and much research is needed to examine the trade-offs for a unified compatible representation of digital video that has negligible distortion, high compression, robustness in the presence of various forms of channel errors, and low receiver complexity. Such an effort will require interdisciplinary cooperation between the consumer electronics, computer, semiconductor, broadcasting and telecommunications industries.

Biography
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