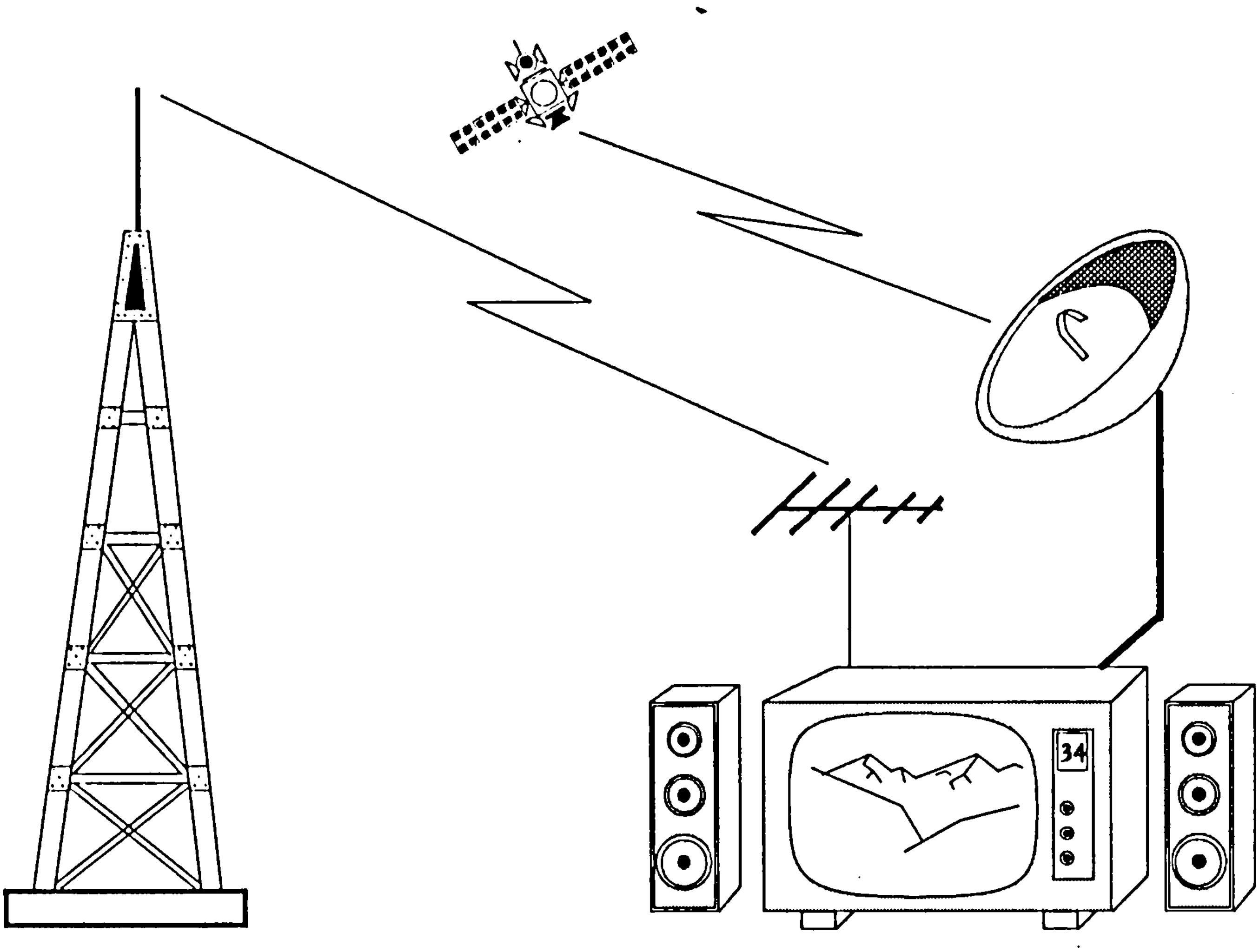
INTERNATIONAL TELECOMMUNICATION UNION

1992 - CCIR RECOMMENDATIONS

(New and revised as of 15 September 1992)



RBT SERIES

BROADCASTING SERVICE (TELEVISION)

CCIR

INTERNATIONAL RADIO CONSULTATIVE COMMITTEE

ISBN 92-61-04591-X

Geneva, 1992

Recommendation 798 (1992)

Digital television terrestrial broadcasting in the VHF/UHF bands

Extract from the publication:
CCIR Recommendations: RBT series: Broadcasting Service (Television)
(Geneva: ITU, 1992), pp. 11-34

RECOMMENDATION 798

DIGITAL TELEVISION TERRESTRIAL BROADCASTING IN THE VHF/UHF* BANDS

(Question 121/11)

(1992)

The CCIR,

considering

a) that Question 121/11 addresses the terrestrial broadcasting of digital [HD]TV signals;

b) that digital television terrestrial broadcasting (which includes HDTV) may be introduced by some countries in the VHF/UHF bands;

c) that the VHF/UHF bands are currently used for analogue television broadcasting (Recommendation 470), and they are quite congested in some countries;

d) that consequently the VHF/UHF terrestrial bands will likely be shared between analogue television broadcasting and digital television broadcasting,

recommends

1. that digital television terrestrial broadcasting should fit in the channels (6, 7 and 8 MHz) intended for analogue television emission in the VHF/UHF bands;

2. that digital television terrestrial broadcasting, as an objective, should not cause interference subjectively greater than that considered acceptable with current broadcasting services in the VHF/UHF bands;

3. that digital television terrestrial broadcasting should have sufficient immunity against interference to be able to coexist with current broadcasting services in the VHF/UHF bands.

Note 1 – Information on current developments in digital television terrestrial broadcasting is given in Annex 1.

ANNEX 1

Digital television terrestrial broadcasting in the VHF/UHF bands

1. Introduction

The majority of established broadcasters use terrestrially-based emission systems operating in the VHF/UHF frequency bands. However, the methods which can be used for the digital coding of high-definition television picture signals and of the associated sound signal in broadcasting from terrestrial transmitters have to be considered and taken into account for the future.

The input and output signals of television systems, at the camera and at the receiver, respectively, are inherently analogue. Thus, the question "why digital?" for television broadcasting is a natural one. While analogue signal degradations are accumulative and difficult to distinguish from the video signal, the ability to regenerate the digital pulse train exactly renders the digital signals theoretically immune to impairments from external sources. Several digital bit streams can be interleaved. This process allows for the emission, transmission, storage, or processing of ancillary signals along with the video. For image compression, the process of redundancy reduction is most effective in the digital domain and is seen, therefore, as the choice for terrestrial HDTV broadcasting.

* VHF/UHF television broadcasting is contained in Bands I-V.

Several administrations have started work on the development of terrestrial digital television broadcasting systems. The quality objectives of these development activities range from conventional television to HDTV. As used in this Annex, the term "digital television terrestrial broadcasting" includes this range of services.

Designing a system for digital television terrestrial broadcasting requires the use of advanced methods for source coding, channel coding and modulation in combination with extensive frequency planning analyses. In addition it is important to consider harmonization with other media.

It should be noted that many of the system concepts, techniques, and concerns described below under geographic headings are relevant worldwide and are being studied in all of the development activities.

2. Developments in Europe

2.1 Introduction

Within Europe, considerable experience has been gained with digital bit rate reduction and modulation techniques, both for video and audio applications. European standards have been developed for the digital exchange of component television programmes at 34-45 Mbit/s and 140 Mbit/s, as a result of work in several European collaborative projects such as EUREKA 256, RACE HIVITS, and the CMTT. A separate project, EUREKA VADIS, aims to develop the technology for the distribution of digital video systems at up to 10 Mbit/s, with a view to standardization within ISO. In addition, much work has already taken place on systems for digital audio broadcasting (DAB), including some very successful demonstrations.

Many European laboratories continue to be active in the field of bit rate reduction, and there is growing interest in applications for television broadcasting. There are now proposals for a major new collaborative project under RACE Task 813 to coordinate this work and to develop techniques suitable for digital terrestrial television broadcasting. The aim will be to seek to combine methods of source coding with channel coding using advanced modulation techniques, and to consider aspects of frequency planning taking into account the particular congestion of the VHF/UHF broadcast bands in Europe. Activities in the field of terrestrial digital HDTV broadcasting are also developing in Sweden and Norway.

2.2 Current activities

2.2.1 Activities in Sweden and Norway

The Swedish Telecom, in cooperation with the Norwegian Telecom and the Swedish Broadcasting Corporation, have started the development of a prototype system for digital terrestrial HDTV. It will be used for experiments and demonstrations over TV transmitters, and the first stage of the project should be accomplished by mid-1992.

It is important to develop an HDTV system that also suits terrestrial networks, because these will be used for a long time to serve a large portion of the population, and also provide the possibility for regional emissions. Such a system can also be adapted to other transmission media such as cable TV networks, TV satellites and future broadband networks. From the consumer's point of view, it is important to establish a future-proof solution with a common type receiver for all transmission media.

The Swedish-Norwegian project should be viewed against this background. It mainly aims at gaining knowledge about digital emission techniques for HDTV and demonstrating the possibilities thereof. At a second stage, the efforts will be concentrated on system aspects and refinements of the various sub-systems.

2.2.2 Developments in the United Kingdom

Within the United Kingdom, a major research programme known as SPECTRE (Special Purpose Extra Channels for Terrestrial Resolution Enhancements) is currently being undertaken for the Independent Television Commission (ITC) by National Transcommunications Ltd. (NTL).

The objective is to determine the most efficient use of the entire terrestrial broadcasting path using digital techniques to exploit as much as possible the redundancy inherent in the current PAL/UHF network which was planned for analogue transmission as long ago as 1961. The research is directed towards methods of digital transmission that could be contained within the standard 8 MHz UHF television channels and which could coexist with the present PAL services. Subjects under study include low bit rate video coding with regard to service quality, also digital modulation methods and the transmission of additional channels within the existing broadcasting bands.

2.2.2.1 Low bit rate video coding and service quality

A motion-compensated hybrid discrete cosine transform (DCT) coding technique has been under development. To compete with high quality satellite distribution, a high quality digital terrestrial service must be able to offer 16:9 aspect ratio component pictures with a minimum source resolution of 720 × 576 samples per frame (luminance).

Recent experience in the bit rate reduction of such pictures using hybrid DCT with motion compensated predictive and interpolative coding has revealed that high picture quality can be maintained for the vast majority of broadcast television picture content at about 12 Mbit/s.

In the absence of transmission errors, the picture quality would be that offered by the low bit rate redundancy reduction coding. Such quality is not constant, but is highly dependent on the statistical content of the picture material being coded. Work is, therefore, continuing on methods of assessing picture sequence criticality in order to develop techniques for determining the service quality of low bit rate coded pictures.

2.2.2.2 Digital modulation methods

Studies have indicated that the only way to achieve band-sharing of a digital transmission with existing analogue services is to radiate the digital signal at a very low level in order that interference is not caused. The digital signal can be at low power because, in the absence of interference considerations, typical carrier-to-noise ratios required for reception are about 15 dB, whereas for the analogue television service a carrier-to-noise ratio of more than 40 dB is needed to provide a grade 4 picture. With the low noise figures now possible for receivers, it may be possible for transmission of a digital signal at 30 dB lower power than the conventional analogue television signal to provide the same coverage. However, a digital signal at such a low power would have to operate in a very hostile interference environment, so that selection of an appropriate modulation scheme is essential.

The particular method under investigation has been the use of orthogonal frequency division multiplexing (OFDM). This consists of a large number of carriers equally spaced in frequency, with each carrier modulated by a digital modulation method such as QPSK. The overall spectrum of an OFDM signal is a good approximation to a rectangular spectrum which just fits multipath propagation. This shape of the spectrum gives excellent results, because the bit-period of each carrier is much longer than the delay of typical reflections. Furthermore, small portions of the transmitted spectrum can be essentially cut out; for example, at the vision and sound carriers frequencies of co-channel analogue transmissions to provide protection between the analogue and digital services.

2.2.2.3 Transmission of additional channels within the existing broadcast bands

A digital service would be able to accept very high levels of interference from the analogue service, so that the frequency re-use distance may be drastically reduced between the analogue and digital services. Studies so far have indicated that perhaps four digital channels could be provided at most main transmitter sites. The studies are continuing.

The situation at relay stations is more complex, since these would occupy frequencies that might otherwise be available for digital transmissions. Nevertheless, present indications are that it is likely to be possible to find channels to broadcast a new digital service from many of the existing stations in the United Kingdom. Transmitters in coastal areas having a short sea-path to an adjacent country are likely to be more difficult to accommodate.

2.2.2.4 Results

On-going studies in the United Kingdom have indicated that digital television technology is likely to be able to make more efficient use of the UHF broadcast spectrum, and possibly offer significant numbers of extra channels which might share the broadcast band with the existing television services.

So far, only QPSK modulation of the OFDM carriers has been examined. There is interest in higher order modulation schemes, particularly 16-level, because of the possibility of conveying a 24 Mbit/s data rate (after error correction) in an 8 MHz terrestrial UHF channel.

Experience gained so far indicates that 12 Mbit/s provides a level of quality approximating to that afforded by MAC, and that about 24 Mbit/s is likely to be required for higher definition pictures suitable for larger screens. Clearly, a variety of possible intermediate options could exist which trade between error performance and picture quality, and studies are continuing.

2.2.3 EUREKA VADIS project (source coding)

An important new initiative on digital TV has been launched within the European "EUREKA" programme for collaborative research: EUREKA 625. More than 30 organizations from 12 different European countries have agreed to cooperate to develop the source coding technology needed to bring all-digital television to the home or office.

The project is known by the acronym VADIS (Video-Audio Digital Interactive System). The word "interactive" reflects the project's interest in making new types of audio-visual services possible, as well as offering improved picture quality and more programme channels from broadcast television.

VADIS will be a major contributor to the international standardization activities such as the current ISO MPEG.

Digital TV gives many benefits in terms of quality and flexibility, but in its raw form occupies a much greater bandwidth than today's analogue signals. The project will develop sophisticated coding techniques to compress digital television signals by a factor of between about 20 and 40 whilst retaining virtually all of the original quality. The compression will allow digital audio-visual services to be carried by digital storage devices, telecommunications networks, terrestrial VHF and UHF channels or satellite channels.

The project has adopted a "generic" approach to the work, i.e. it aims to develop a solution which can be used across a wide range of applications. Initial investigations will be carried out by computer simulation; field trials using experimental equipment are planned for 1993.

The project work has been divided into five work packages:

- requirements, the function of this Working Party is to define the requirements of the range of applications to be considered by the VADIS project;
- algorithms;
- system aspects, the main objective of this Working Party is to define a method for multiplexing the video, several audio, and other data streams into a single bit stream, while maintaining audio and video information in synchronism;
- demonstrators/VLSI; and
- field trials using laboratory prototype equipment are planned to be carried out during 1993.

2.2.4 European project RACE 813 (channel coding and modulation)

For digital television broadcasting, taking account of the specific European situation which involves a high degree of emphasis on closely coordinated frequency planning, specific studies on the feasibility of digital terrestrial broadcasting have to be made, and major European broadcasters and consumer manufacturers are currently preparing a project for this purpose; some of the partners of this project have already started some implementations and investments in this area, and a structured coordination is therefore necessary.

The main goal of the project is to contribute to the establishment of a European standard and corresponding technologies for a digital television terrestrial broadcasting service. The general strategy of the establishment of the service should be made by a European Strategy Group, also in preparation, involving manufacturers, broadcasters and the EBU.

The project itself will concentrate its activities on channel modulation/coding and broadcast systems aspects and covers the following areas.

Firstly, a broad study which will investigate all possible data rates within existing terrestrial VHF and UHF channels in order to determine which digital video broadcasting services and products are feasible. The purpose of this study is to ensure that account is taken of all possible future options, such as more TV channels and/or higher picture quality.

Secondly, as a first step towards defining a service/product, demonstrators will be constructed for broadcast TV programmes and will be aimed at serving portable, i.e. plug-free, or mobile receivers. These demonstrators will provide for investigation of network configuration aspects, extensibility for future services, frequency allocations aspects, chip area analysis, aiming for a service with a quality higher than that of current PAL and SECAM systems and which will include a 16:9 capability.

The project mainly addresses TV broadcasting over UHF/VHF channels keeping in mind that further adaptation will be studied for other bandwidth limited media. The project has been divided into seven work packages: management and coordination, system aspects and requirements, channel coding and modulation, multiplex architecture and network aspects, tests and measurements, development of demonstrators, developments of ICs.

It is assumed that the format of the digitally coded video and sound signals will be developed and defined within the scope of another project or by other groups. Therefore, in this project, the performance is evaluated mainly in terms of available data rates, and of transmission error ratios.

Among the conditions to be realized, the digital multiplex must be adequately flexible in order to fit different applications or service configurations, and to enable future modifications. The system must be designed such that a later expansion to high-definition television is possible in a compatible way. This activity involves 22 participants from seven countries.

3. Developments in North America

3.1 Introduction

The United States of America and Canada are in the process of choosing a standard to be used by terrestrial broadcasters to provide an advanced television service. In the two countries, a major, extensive joint testing programme is in progress and will last until the summer of 1992.

In the United States of America, the Federal Communications Commission (FCC) created an Advisory Committee on Advanced Television Service (ACATS) to develop a technical record concerning the proposed systems and to make recommendations to the FCC. The final choice is scheduled to be made by the FCC during the first half of 1993.

The FCC has ruled that HDTV will need to fit within the 6 MHz channels in the VHF and UHF bands now used for conventional TV. Hence, there will be the conventional TV channels and additional HDTV channels which will interfere with each other in the TV bands.

In June 1990, the first all-digital terrestrial broadcasting HDTV system was proposed and submitted to the FCC for consideration as a potential United States' standard. Since then, three more all-digital systems have been developed and proposed for evaluation. Parameters of the current four proposed systems are given in § 3.6.2.

It is claimed that an all-digital system will provide true high-definition quality with no perceptible degradation caused by noise or interference up to the edge of its coverage area which is equivalent to the coverage of NTSC. Less transmission power may be required and the signal is easy to encrypt.

3.2 Source coding

3.2.1 Introduction

The latest VLSI developments have significantly contributed to the rapid emergence of digital image compression techniques in HDTV applications. Significant progress has been made in the development of advanced television techniques for over-the-air broadcasting. The fundamental goal of digital HDTV compression is to reduce the bit rate while maintaining an acceptable image quality. Numerous bandwidth compression techniques have been developed, such as differential pulse code modulation (DPCM), sub-band coding including transform coding, vector quantization, hybrid coding, and adaptive versions of these techniques, in response to the growth of image-processing methods. These techniques usually explore the psychophysical as well as statistical redundancies in the image data to reduce the bit rate. In this section, a review of some digital HDTV compression techniques which are employed in the systems proposed in the United States of America is presented.

A major objective of source coding is to represent an image with as few bits as possible while preserving the level of quality and intelligibility required for the given application. Source coding consists of motion prediction/compensation, transformation, quantization, and entropy coding. The process is applied to the picture source material and yields results which are lossy, i.e. some picture information is lost. Each of these elements attempts to exploit the redundancy present in the source image and the limitations of the display device and the human visual system. Source coding of moving pictures can be further divided into intrafield/frame and interfield/frame* coding.

3.2.2 *Intraframe coding*

Video can be considered as a sequence of frames in which each frame is a rectangle of pixels. Intraframe coding codes each television frame based on the information from that frame only. It removes only the spatial redundancy within a frame. Three widely used coding approaches are of the intraframe coding type; they are predictive coding, transform coding and vector quantization.

One type of predictive coding which is used widely is DPCM. In DPCM, a prediction of the current pixel intensity is obtained from one or more previously coded pixel intensities. DPCM schemes can be made adaptive in terms of the predictor or quantizer. One major advantage of DPCM over transform coding is its simplicity. In addition, at low compression ratios, the bit rate reduction that can be achieved by waveform coding is comparable to that of transform coding. An example is studio applications of HDTV where high quality images are required.

In transform coding, an image is transformed to a domain significantly different from the image intensity domain, and the transform coefficients are then coded. Transform coding techniques attempt to reduce the correlation that exists among image pixel intensities more fully than do waveform coding techniques. When the correlation is reduced, redundant information does not have to be coded repeatedly. Transform coding also exploits the observation that for typical images a large amount of energy is concentrated in a small fraction of the transform coefficients. This is called the energy compaction property. Because of this property, it is possible to code only a fraction of the transform coefficients without seriously affecting the image. Another desirable property of a transform is the reduction of correlation among transform coefficients, called the correlation reduction property. By proper choice of the basis function, the correlation among the coefficients can be reduced. An example of a transform is the discrete cosine transform (DCT) which is the most widely used transform in image coding. In DCT coding, an image is divided into many sub-images or blocks (typically 8 pixels by 8 pixels), and each block is coded separately. By coding one sub-image at a time, the coder can be made adaptive to local image characteristics. For example, the method of choosing quantization and bit allocation methods may differ between uniform background regions and edge regions. To take advantage of the energy compaction property, two approaches are widely used to determine which transform coefficients to code; they are zonal coding and threshold coding. In zonal coding, only the coefficients within a specified region are coded. In threshold coding, transform coefficients are compared with a threshold, and those above the threshold are coded. The choice of which transform coefficients are to be coded depends on local image characteristics and can be controlled on the basis of buffer status.

Sub-band transforms are generally computed by convolving the input signal with a set of bandpass filters and decimating (down-sampling) the results. Each decimated sub-band signal encodes a particular portion of the frequency spectrum, corresponding to information occurring at a particular spatial scale. An adaptive bit allocation algorithm that distributes the bits among the sub-bands will make the sub-band coding scheme suitable for a wide variety of images.

In vector quantization, a wide range of image material is processed to yield a finite number of image vectors (image blocks like those used in transform coding). Properly selected, this finite set can be used to reconstruct the original images with little degradation. For example, transform coding can be considered to produce those vectors representable by low order cosines. In vector quantization, images to be transmitted are resolved into vectors and the

---

* Differences in terminology arise depending upon the use of interlace or progressive scanning. This Annex will not make such distinctions and will use only the terms intraframe and interframe.

stored vector set, or codebook, is searched for a suitable match to each source vector. Compression is achieved by transmitting the vector address rather than the image data. Only with recent research in large codebooks has vector quantization been recognized as a powerful image coding technique.

To further increase coding efficiency, variable-length entropy coding is used in the video multiplex coder which immediately follows the source coder. The resulting data stream of the above coding scheme does not have a fixed bit rate; the amount of data reduction depends on the effectiveness of the coding. However, a fixed bit rate is demanded by transmission. Therefore, the output of the video multiplex coder is sent to a buffer, which regulates the flow of video information to a fixed bit rate by controlling, among other parameters, the quantization.

DCT coding is used in the DigiCipher, DSC-HDTV, and ADTV systems. Sub-band coding is used in the ATVA-P system.

3.2.3 *Interframe coding*

Interframe coding is used in all of the proposed digital HDTV terrestrial broadcasting systems to obtain a higher compression rate than is achievable with intraframe coding alone by reducing the temporal redundancy between pictures. To reduce the temporal redundancy of pictures, the residual of the current frame and the predicted current frame is coded. The predicted frame is generated based on information from a previous and/or future frame. Motion prediction/compensation is used to estimate the current frame so as to make the residual as small as possible. The motion information is part of the necessary information to recover the picture and has to be coded and transmitted appropriately.

All of the coding methods mentioned in the previous section can be used to code the residual pictures. The encoded picture information along with the motion information is further compressed using variable-length coding to achieve maximum efficiency. As with intraframe coding, a fixed data rate can be obtained by using a buffer.

Motion prediction methods may be classified broadly into two groups, that is, block matching and spatio-temporal constraint methods. The block matching methods involve considering a small region in an image frame and searching for the displacement which produces the "best match" among possible regions in an adjacent frame. Algorithms of the spatio-temporal constraint methods are based on the spatio-temporal constraint equation.

Block matching methods are used in the DigiCipher, DSC-HDTV, and ADTV systems. The ATVA-P system employs the spatio-temporal constraint method.

3.2.4 *Quantization*

The process of assigning a specific continuous scalar quantity to one of several discrete levels is called quantization. If each scalar is quantized independently, the procedure is called scalar quantization. If two or more scalars are quantized jointly, the procedure is called vector quantization (VQ). A major advantage of vector quantization is that it can exploit statistical dependence among the scalars in the block. Vector quanitization is used in DSC-HDTV systems to represent the possible combinations or patterns of quantizers which can be applied to a given block of coefficients.

Adaptive quantization is used in all of the proposed systems to optimize the source coding.

3.2.5 *Entropy coding*

Statistically, certain values appear more frequently than others. It is possible to assign a shorter codeword to those values occurring frequently and a longer one to those occurring less frequently. From information theory, the entropy is the theoretically minimum possible average bit rate required in coding a message. One optimal codeword design method which is simple to use, which is uniquely decodable, and which results in the lowest average bit rate is Huffman coding (variable-length coding). Also, when the transform/sub-band coefficients are properly scanned, the coefficients tend to be ordered from high amplitude to low amplitude, with the result that zero coefficients typically appear as a single long run which can be coded by a short codeword.

Entropy coding is used in all of the proposed digital HDTV systems to code coefficients of the image itself and image related ancillary information.

3.2.6 *Buffer*

Due to the entropy coding (variable-length coding) and the adaptive quantization, the data rate from the source coding varies locally. A buffer is used to regulate the variable input bit rate into a fixed output bit rate for transmission. The state of the buffer is calculated periodically and relayed back to adjust the quantization level.

Buffers are employed in all of the proposed digital HDTV systems.

3.3 *Channel coding*

3.3.1 *Introduction*

In order to transmit the HDTV signal in 6 MHz, the four United States' digital HDTV proponents are reducing the video data rate of HDTV to 15-17 Mbit/s, a compression ratio of approximately 60-70 times. The high compression dictates that channel coding be employed to avoid block errors and multiframe error propagation. High efficiency in channel utilization required by the 6 MHz limitation means that the channel must be properly equalized and that the multipath and interfering signals must be severely limited. The terrestrial broadcast channel is a very difficult medium as witnessed by the transmission impairments of conventional television such as noise, ghosts, interference and frequency distortion. The currently proposed digital HDTV systems use channel coding to protect data that must be correctly received. The channel coding techniques used for error reduction include data interleaving, error detection and replacement and error correction at different levels of protection for bits and blocks of unequal importance.

3.3.2 *Multiplexing of vision, sound and data*

The effective information data rate for the different proponents range from 15-17 Mbit/s for video (depending on transmission mode), 0.5 Mbit/s for audio and 250-550 kbit/s for data. Randomization is performed on the digital data so that the equalizer in the receiver performs properly and a noise-like interfering signal is generated. Data interleaving is performed by some proponents so that bursts of channel bit errors can be treated as uncorrelated bit errors by the forward error correction codecs. Digital HDTV proponents have different video, audio and data bits per data frame, superframe, and subframe levels. Synchronization bit sequences are inserted at intervals to mark these boundaries and provide appropriate video, audio, data/text and control data streams to the processor.

3.3.2.1 *DigiCipher system*

Prior to forward error correction at the encoder, the line time for each pair of video lines includes 848 information bits for the 16-QAM mode and 1 160 information bits for 32-QAM. Line pair 1-2 consists of 8 bits for access control, 8 bits for ancillary data, 32 bits for audio, 24 bits for synchronization, 40 bits for system control, and the remainder for video. Line pairs 3-4 through 1 049-1 050 consist of 8 bits for access control, 8 bits for ancillary data, 32 bits for audio, and the remainder for video. The total data rate, before error correction, is 13.34 Mbit/s for the 16-QAM mode and 18.22 Mbit/s for 32-QAM.

3.3.2.2 *DSC-HDTV system*

The DSC-HDTV signal is encoded into a digital signal at a rate up to 21.0 Mbit/s or 2.69 Mbytes/s.

The transmission bytes are arranged in a "data frame" timed identical to an NTSC frame. One data frame contains two "data fields" and one data frame is divided into 525 "data segments" all in correspondence with NTSC "frame", "field" and horizontal line, respectively. (These new transmission signal terms avoid confusion with "frame", "field" and "line" pertaining to source and display signal.)

One data segment contains 171 bytes, four of which are sync bytes. The first byte of these four is intended to synchronize the receiver video data clock. Each data field is preceded by a data field sync signal of one data segment duration consisting of pseudo-random data sequences. This signal is used for field synchronization but also as a training signal for a ghost-canceller/channel-equalizer in the receiver. The rest of the data field is occupied by programme and service data to which are added Reed-Solomon bytes for forward-error correction. The sync bits are not protected by the R-S code but have their own protective redundancy. The bit allocation is: video at 8.6 to 17.1 Mbit/s, audio at 0.5, ancillary data at 0.413, Reed-Solomon protection at 1.3 to 2.4, sync at 0.292 to 0.544, and unassigned at 0.04 for a total of 11.1 to 21.0 Mbit/s.

3.3.2.3 *ADTV system*

ADTV's cell-relay-based data-transport layer supports the prioritized delivery of video data, thus providing graceful service degradation under impaired channel conditions. The cell relay provides logical synchronization that is essential for reliable delivery of variable-length-coded compressed video in the presence of transmission errors. ADTV's data transport protocol also offers service flexibility for a wide mixture of video, audio, and auxiliary data services. The system allocates 14.98 Mbit/s for video, 512 kbit/s for audio, 40 kbit/s for data, and up to 512 kbit/s for ancillary data. However, ADTV's multiplexing of video, audio and data is flexible, and the entire capacity may be allocated among these as desired.

The prioritization process identifies pieces of information that are more critical in terms of the "type" of data element (video data elements include motion information, block type, DCT coefficients, quantization parameters, etc.). The priority processor assigns different priority to each data element according to an assignment rule. The assignment is made dynamically, reflecting any fluctuation in the channel load. In general, the load on the channel will vary in time because of the variable output rate of the compressed video data.

A transport format has been developed specifically to handle information with different error protection requirements over a simulcast channel. Data encapsulation to support a prioritized transport is designed to provide payload chaining and segmentation capability in order to maximize channel utility and minimize the impact of payload losses on the system. The transport processor asynchronously multiplexes the payload data with different priorities into basic transport units called cells. A cell resembles a data packet in conventional packet networks in modern data communication. It has a header and a trailer enclosing a payload area. Each cell has a fixed size and its own error control bits. It is noteworthy that ADTV's cell format is easily transcodable to B-ISDN (broadband integrated services digital network), thus providing a path for future information services.

3.3.2.4 *ATVA-P system*

The 15.64 Mbit/s of digital video information is multiplexed together with 0.5 Mbit/s for 4 digital audio channels, an auxiliary 0.126 Mbit/s data stream, and 0.126 Mbit/s access control to form the composite 19.43 Mbit/s digital stream when error correction is added. The auxiliary data stream is made available for transmission of closed captions or other digital data. Sync bits are inserted into the transmitted bit stream in order to mark the frame boundaries. These unique bit sequences are used by the receiver to establish frame synchronization. The encoder performs encoding of one frame at a time. The digital data in each frame is transmitted in the following order: frame sync, motion vectors, audio channels, auxiliary data, modulation and video coefficients. This basic frame structure is repeated for every frame.

Prior to transmission, the digital data is processed with a sequence randomizer which randomizes the transmitted bits. The sequence randomizer is implemented as a linear recursive generator with a generator polynomial of $1 + \chi^{-18} + \chi^{-23}$. Randomizing is performed on the digital data in order to guarantee that the transmitted sequence of bits is sufficiently random so the adaptive equalizer in the receiver remains properly converged during periods of idle transmission.

3.3.3 *Error protection*

In addition to error detection embodied in the cyclic redundancy check codes used in some systems, all systems use forward error correction (FEC). All proposed systems use Reed-Solomon FEC coding. Reed-Solomon codes are one of several classes of block codes known for their powerful error correcting capability. Reed-Solomon code of block length N, K data bits and error-correcting ability of T or fewer can be described as rate K/N ($t = T$).

The DigiCipher system employs Reed-Solomon coding at a rate of 106/116 ($t = 5$) for 16-QAM and 145/155 ($t = 5$) for 32-QAM in addition to trellis coding with rate 3/4 for 16-QAM and rate 4/5 for 32-QAM. System threshold is 12.5 dB *C/N* for 16-QAM and 16.5 dB *C/N* for 32-QAM including 2.5 dB of implementation margin. The error correction data accounts for 6.17 Mbit/s.

A data segment in the DSC-HDTV system contains a total of 171 bytes of data. With four used for sync every data segment, a total of 167 bytes is available for information and error control. Twenty bytes are set aside for Reed-Solomon coding at a rate of 147/167 (t = 10). This allows correction of a maximum of ten errors per data segment, exactly half the number of parity bytes. The threshold for visible errors is reached at a signal-to-noise ratio of 16 dB for 4-level data and 10 dB for 2-level data. The "data field" (vertical) sync consists of a pseudo-random data sequence of one "data segment" (horizontal line) duration and also serves as the reference for a ghost-canceller/channel-equalizer in the receiver.

The ADTV system applies Reed-Solomon coding to the data bytes. Depending on the priority, different amounts of FEC is applied to the data. In addition, data byte interleaving is performed as part of the channel coding operations. This ensures that bursts of channel errors can be treated as uncorrelated random bit errors, which can often be corrected by the Reed-Solomon codes.

The ATVA-P system employs Reed-Solomon coding at a rate of 130/154 (t = 12) to correct transmission errors. The system threshold is 19 dB *C/N* including 2.5 dB of implementation margin. At 19 dB *C/N* there will be one undetected error event per day. The error correction data accounts for 3.59 Mbit/s. Error propagation is limited to within a block, and the systems are capable of regaining synchronization every frame time.

3.4 *Modulation*

3.4.1 *Introduction*

The transmission of data in digital form has long been known to offer advantages over analogue transmission. With digital transmission, only when the noise is high enough to change zeros into ones or ones into zeros, does noise interfere with perfect delivery. Forward error correction techniques now available go a long way to prevent corruption of the signal by the occasional error that moderate levels of noise can cause. However, the digital transmission system must deal with the high data rates that digital encoding creates. A high-definition TV signal digitized to 8 bits per sample creates a data stream of approximately 1 Gbit/s. The digital compression (source encoding) being considered in the United States of America reduces the data rate to about 17 Mbit/s, a reduction factor of about 60 times. The technology for implementing this level of compression did not exist even a few years ago.

3.4.2 *Methods of digital modulation*

Digital modulation is an outgrowth of the more familiar methods of analogue modulation such as amplitude, frequency, and phase modulation. Digital modulation techniques were first developed for telephone modems and for satellite transmission of data. Although the bandwidths available in these two technologies range from audio to tens of MHz, the same theory applies. The high data rate required by HDTV, about 20 Mbit/s after compression and error correction, coupled with the need to confine the radiated spectrum to a 6 MHz TV channel, make it necessary to use that channel as efficiently as possible.

3.4.2.1 *Quadrature amplitude modulation (QAM)*

Three of the four proposed digital systems, DigiCipher, ADTV, and ATVA-P, use QAM. 16-QAM is a digital form of quadrature amplitude modulation that transmits four bits per symbol (4 bit/Hz). The approximately 20 Mbit/s data stream is first converted into 4-bit words called symbols. The "16" in the title refers to the fact that there are 16 different possible symbols. The symbol rate is clearly one quarter of the original bit rate, or about 5 Msymbol/s. A simple D-to-A converter converts one pair of bits from the symbol to a four-level signal that is applied to a balanced modulator along with an RF (or IF) carrier to the other input. The other pair of symbol bits is similarly converted into a four-level signal, and is applied to a second balanced modulator operating in quadrature from the first, that is with the carrier shifted 90°. The two balanced-modulator outputs are combined to produce the 16-QAM signal, centred at the carrier (or intermediate frequency). This output signal will then be heterodyned to the actual transmitted frequency.

At the receiver, there is also a pair of balanced modulators, driven by a local oscillator (LO) shifted by 90° between modulators. The LO must be phase-locked to the original carrier at the transmitter. In the receiver, the carrier phase is recovered from the data by a complex process using phase-locked loops and will not be discussed here. The outputs of the balanced modulators are not square waves, but are rounded versions of the four-level modulating square waves, due to filtering for the channel bandwidth limitation. In the 16-QAM receiver, the in-phase signal and the quadrature signal, both four-level signals, are each converted back to two-bit digital form by a pair of A-to-D converters. The resulting two pairs of bits are then multiplexed to yield a replica of the original 20 Mbit/s data stream.

3.4.2.2 The RF spectrum

To estimate the bandwidth of the transmitted signal, consider the busiest possible modulation signal going into one of the balanced modulators. This would be data at 5 Mbit/s, alternating between zero and one, which is just a square wave at 2.5 MHz. If we band-limited this signal to just over 2.5 MHz, the output of the balanced modulator would be 5 MHz wide, just right to fit in a 6 MHz channel with 0.5 MHz guard bands. Alternatively, we could leave the 4-level modulating signal unfiltered, and filter the 6 MHz channel, with the same effect. The RF energy resulting from the alternating data pattern is concentrated at the two frequencies, 5 MHz apart, near the guard bands. For the actual data, lower modulating frequencies are also present, loading energy throughout the channel.

Because of the source coding and the channel coding, the modulating data appear random, even when the video is not. This results in RF energy spread throughout the 6 MHz band, as if it were band-filtered noise. Signals of this type are extremely robust against co-channel interference, for just the reasons that led to spread-spectrum technology. Because discrete carriers are absent, they also tend to cause much less interference to other signals than do NTSC, PAL or SECAM signals of equivalent power. Furthermore, it is expected that the lower signal-to-noise ratio needed for digital transmission will make it possible to use less transmitted power. These considerations combine to make possible the use of the wasted (taboo) channels in the current allocation plans, with the result that many new digital HDTV channels can be added to what had so far been the filled TV spectrum.

3.4.2.3 Vestigial sideband modulation (VSB)

One proposed system, DSC-HDTV, uses 4-VSB and 2-VSB modulation. Vestigial sideband, which is used for NTSC transmission, is a workable compromise between double-sideband AM and single-sideband AM. Single-sideband cannot be used with analogue TV because of practical problems with the very sharp cut-off filtering needed at very low frequencies, though it is very practical for audio transmission where low frequencies can be attenuated. Double-sideband simply requires too much bandwidth for TV. Vestigial sideband includes a small part of the lower sideband with the full upper sideband. Sloped filtering at the transmitter and/or at the receiver attenuates the lower end of the band to compensate for the duplication of low-frequency sidebands. For analogue VSB-TV, the carrier is not suppressed.

VSB is not normally listed among digital modulation methods, nor is it normally used with a suppressed carrier. Since the nature of VSB makes it much more difficult to recover a suppressed carrier from VSB than from QAM, a pilot carrier is needed. The proponent chose VSB because of the desire to transmit a pilot carrier at the suppressed carrier frequency to improve channel acquisition at the receiver under noisy conditions. A pilot carrier with QAM would be in the centre of the 6 MHz band, and could cause interference into NTSC. For VSB, the carrier is near the bottom of the band, where NTSC receivers have their own VSB filters with strong attenuation.

Since VSB modulation transmits only one full sideband, that sideband can span almost the entire 6 MHz channel. Hence, the symbol rate (the modulation rate) must be doubled over that for QAM for efficient use of the channel. Since VSB lacks the ability to carry a quadrature channel, 4-VSB and 16-QAM permit about the same data rate when each is optimized to the channel in its own manner.

3.4.2.4 Modulation in proposed systems

DigiCipher provides two transmission modes, 32-QAM at a rate of 24.39 Mbit/s and 16-QAM at a rate of 19.51 Mbit/s. The mode is selectable by the broadcaster; 16-QAM has a wider coverage area, while 32-QAM provides higher video quality and receivers will automatically configure to the mode being transmitted. It is claimed that the 32-QAM mode provides essentially error-free reception at a carrier-to-noise ratio of 16.5 dB; for the 16-QAM mode, this threshold is 12.5 dB. The symbol rate is 4.88 Msymbol/s.

DSC-HDTV uses a combination of 4-VSB and 2-VSB modulation, meaning four-level and two-level vestigial sideband modulation. The symbol rate is 10.76 Msymbol/s. Some data are transmitted at 1 bit/symbol and other data are transmitted at 2 bit/symbol. The resulting data rate ranges from 11.1 to 21.0 Mbit/s. A pilot carrier is used, and better signal acquisition under noisy conditions is claimed because of it.

ADTV uses 16-QAM at a rate of 21 Mbit/s. The symbol rate is 5.25 Msymbol/s. Spectral shaping is said to reduce interference to and from NTSC.

ATVA-P uses 16-QAM at a rate of 19.43 Mbit/s. The symbol rate is 4.86 Msymbol/s. They claim essentially error-free reception, one undetected error event per day, at a carrier-to-noise ratio of 19 dB.

3.4.3 Channel equalization

The DigiCipher HDTV receiver uses a 256 tap adaptive equalizer to handle multipath distortions. It can handle single or multiple echoes with the range −2 to +24 μs.

DSC-HDTV has an automatic ghost-canceller/channel-equalizer. Multiple ghosts can be handled over the range of −4 to +20 μs.

ADTV is equipped with an adaptive channel equalizer to combat the effects of multipath propagation and ghosts. It is designed to work up to 16 μs, and may be extended to work up to 40 μs.

ATVA-P uses adaptive equalization to handle multipath reflections found in typical terrestrial broadcasting, and microreflections found in cable TV. The equalizer will cancel complex multipath of up to 2 μs, as well as a single long multipath reflection of up to 32 μs.

3.4.4 Spectrum shaping

DigiCipher and ATVA-P use a linear-phase, finite-impulse-response digital filter for spectrum shaping.

DSC-HDTV uses preprocessing at the encoder for the NTSC interference filter in the receiver. It also has skirt selectivity the same on the vestigial sideband side as on the high-frequency side. The skirt selectivity is divided between the transmitter and the receiver, an arrangement said to be the optimum one for signal-to-noise ratio. Dispersion is used to prevent the periodic data segment sync from causing interference into NTSC.

ADTV uses spectrally-shaped QAM (SS-QAM) to achieve its goals of high spectral efficiency and NTSC-robust and NTSC-friendly operation.

3.5 Spectrum accommodation

3.5.1 Introduction

In the United States of America active consideration is underway to provide for the terrestrial emission of HDTV signals in the existing VHF/UHF allocations. Analyses show that it may be necessary to reduce co-channel spacings to a minimum of 160 km if the vast majority of existing terrestrial broadcasters (greater than 97%) are to be accommodated with an HDTV service in addition to their NTSC capability. HDTV coverage and acceptable co-channel interference levels of these spacings are currently under investigation.

This section sets forth some of the techniques which are expected to be used to determine if there is sufficient spectrum to provide for these additional services. They include assessments of the need to maintain UHF taboo restrictions currently applied to NTSC, analysis of effective coverage areas, and development of allotment/assignment methodologies.

3.5.2 Taboo assessment

When the UHF allotment plan for the United States of America was developed in the early 1950s, restrictions were placed on certain channel separations in order to accommodate the interference limitations existing at that time in the NTSC transmission/receive systems. These interference limitations were termed taboos. The nature of these taboos is described in § 3.5.5. A preliminary assumption has been made that the way to provide sufficient additional spectrum in the VHF/UHF bands for the new terrestrial HDTV service is to use minimum co-channel spacings of 160 km and avoid the application of taboo restrictions. In this case virtually all (greater than 97%) of the currently existing (approximately 1700) NTSC terrestrial broadcast stations can be provided with an HDTV assignment. Since it would be desirable to avoid taboo restrictions, it is important to understand the interference characteristics of the proposed HDTV systems and whether the continued protection of certain taboo channels is required. An algorithm was developed to analyze the effect on possible allotment plans of retaining certain taboos. The scenarios analyzed are described below. The allotment plan scenarios were all carried out under the assumption of 160 km co-channel spacing. They are all based strictly on geometric considerations (160 km co-channel spacing and the taboo distances) and make no assumptions regarding interference immunity. Note in § 3.5.5 that taboo rules are expressed in distance (km) not D/U ratios. Except for the oscillator taboo (*n* + 7), all the taboo mechanisms described in § 3.5.5 were used in the analysis described here.

3.5.2.1 HDTV/NTSC scenario

The HDTV/NTSC scenario examines the impact of both individual and multiple taboos on the availability of spectrum by applying the taboo separation restrictions equally to both existing NTSC stations and newly assigned ATV channels. This scenario is the most restrictive of the three scenarios.

3.5.2.2 NTSC scenario

The NTSC scenario examines the availability of HDTV spectrum by applying the taboo separation restrictions for new HDTV channels only to existing NTSC assignments. It assumes that the new HDTV receivers will incorporate new and improved design and manufacturing tolerances that will virtually eliminate these interference effects for the new HDTV service.

3.5.2.3 NTSC/collocation scenario

The third scenario examines the availability of HDTV spectrum by applying the taboo separation restrictions only to existing NTSC assignments as in the NTSC scenario; however, it allows for exact collocation of the taboo channel with the associated NTSC channel. This scenario is the least restrictive of the three scenarios.

Table 1 shows the number of assignments which are lost for each of the three scenarios when various combinations of the taboos are retained.

TABLE 1

Combined results of scenarios and taboos

Taboo	HDTV scenario (1)	NTSC scenario (1)	NTSC/collocated scenario (1)
n ± 1	93	63	30
n ± 1, +14, +15	338	156	75
n + 2, ± 3, ± 4, ± 5	70	50	3
n + 4, ± 7, ± 8	19	11	1
n ± 2, ± 3, ± 4, ± 5, ± 7, ± 8	135	98	11
n ± 1, ± 2, ± 3, ± 4, ± 5, ± 7, ± 8, +14, +15	483	304	153

(1) The value denotes the number of HDTV assignments that are lost by retaining the indicated taboos, in other words, the number of stations which could not be accommodated.

3.5.2.4 Conclusions

The results of these analyses led to the following conclusions:

- full HDTV accommodation for existing licensees is not possible if all the NTSC taboos are retained. Using the third taboo scenario described above, only 91% of all existing licensees can be accommodated. Under the first scenario, the percentage decreases to 72%;
- regardless of which scenario was examined, the picture image taboo (n + 15) was determined to achieve the worst accommodation statistics for HDTV, while the IF-beat taboos (n + 4, ± 7, ± 8) exhibited the best;
- except for the image taboos (n + 14, n + 15), the effect of changing the taboo separation restrictions has little impact on the HDTV accommodation statistics;
- allowing exact collocation of the taboo channel improves the HDTV accommodation statistics. Near collocation of the taboo channels provides moderate improvement to the ATV accommodation statistics in the case of the adjacent and image taboos; however, near collocation significantly improves the statistics for all other taboos.

3.5.3 Coverage and interference analyses

The subject of greatest concern for a broadcast station is the extent of the coverage area. The original NTSC allotment plan was constructed based on theoretical noise limited considerations modified in some geographical regions to be interference limited to accommodate additional stations. In practice some of the existing stations have coverage areas which are further limited by interference. In considering coverage for a digital HDTV system the objective has been to provide a comparable coverage area. Techniques to optimize coverage by HDTV services are currently under development. A desirable objective is that an HDTV station would have the same coverage as the companion NTSC station at the same location.

3.5.3.1 NTSC coverage

The locations and spectrum allotments of the NTSC stations were determined on the basis of separation distances and limits on transmitter power and antenna height. Figures 1 and 2 indicate the number of currently existing NTSC VHF and UHF stations whose Grade B service is affected by co-channel and adjacent channel stations, respectively.

3.5.3.2 HDTV station service area

Given the need to have close spaced HDTV stations, it should be expected that the HDTV station service areas will be interference limited. The FCC's Advisory Committee is developing two techniques:

- to determine an HDTV service area equivalent to that of an NTSC station, and
- to allow determination of service area as a function of the interference characteristics of the proposed systems whose characteristics are now being determined by the Advanced Television Test Center (ATTC).

  The ATTC is measuring D/U ratios of HDTV into NTSC, NTSC into HDTV, and HDTV into HDTV. On the basis of the D/U ratios obtained, models will be developed to estimate coverage areas compatible with current NTSC broadcast services.

3.5.3.3 Effective service area

The effective service area of a TV station is the area resulting as a consequence of the interference contours impinging on its service area from other television stations.

3.5.3.4 Proponent service area

Methods are being developed which will define the coverage area available from a particular proponent system in the presence of NTSC interference. This will be accomplished using a model which takes the receiver interference and noise thresholds of the proposed systems measured by the ATTC and relates them to the service and interference areas.

FIGURE 1

Distribution of the number of co-channel stations impacting the grade B service of existing NTSC stations

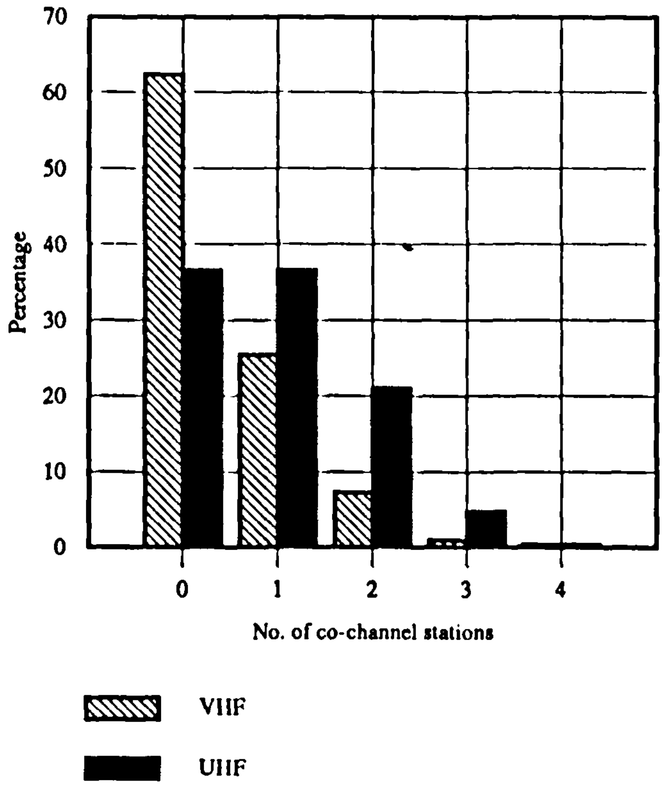
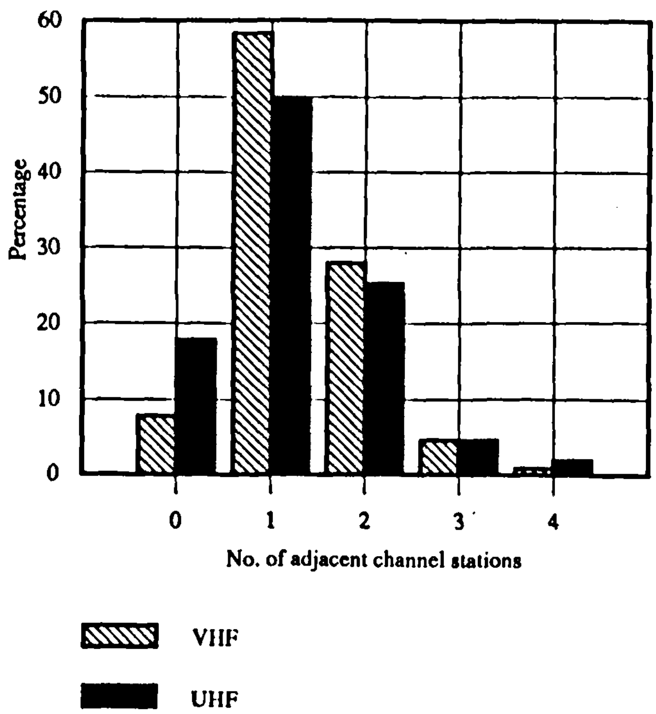


FIGURE 2

Distribution of the number of adjacent channel stations impacting the grade B service of existing NTSC stations



3.5.4 Assignment/allotment plan

To develop a plan for the HDTV allotments, certain assumptions or principles need to be recognized. From these an allotment plan can be developed.

3.5.4.1 Principles

Principles under consideration by the FCC Advisory Committee as a basis for HDTV allotment planning are:

a) *Pair ATV allotments with existing NTSC allotments*

An HDTV channel should be identified and associated with each of the existing VHF and UHF allotments. This provides the fundamental basis for an HDTV plan, and serves as a baseline for implementation.

b) *Comparable coverage*

A desirable objective of the allotment plan (when implemented to become actual assignments), is that it be capable of providing all existing NTSC stations with an HDTV service area comparable to the present interference limited service area of the stations with which it is paired.

c) *Use existing sites*

To the extent possible the assignment plan should be constructed, predicated on the use of the existing transmitter site locations for the transmission of the HDTV signal.

d) *Separation limits*

The allotment plan is currently being developed primarily on the basis of minimum separation distances between co-channel stations.

e) *Allotment models*

As there are literally thousands of possible combinations of pairings possible of HDTV allotments with NTSC allotments, optimization algorithms need to be used to determine a feasible distribution of allotments.

f) *Taboo spectrum*

The VHF/UHF spectrum not being used as a consequence of taboo considerations in the existing NTSC UHF/VHF allotment plans may be selectively employed as necessary to provide for HDTV allotments.

g) *HDTV/NTSC interference*

An objective of the HDTV plan is to minimize interference from an HDTV station into an NTSC or another HDTV service area. A desirable goal is that the level of predicted interference be perceived to be no greater than what is currently considered as acceptable interference between existing NTSC stations.

h) *Freeze NTSC assignment parameters*

In order to know the frequency, and space dimensions available for development of the HDTV plan, certain variables in the existing NTSC allotment implementation should be frozen at some fixed time. This means freezing, at some point in time, the existing transmitter locations. Doing so will help establish the boundary conditions, within which the HDTV plan may be developed.

j) *Vacant allotments*

The spectrum presently allotted but not used may be needed to obtain full ATV accommodation for all existing on-the-air stations. Thus, to the extent necessary, a minimum of such allotments may need to be utilized. The affected number of vacant allotments should be kept as small as possible, being used only when an operating assignment would be prevented.

k) *Receiving system*

The characteristics of a typical HDTV receiving system should be taken into account in determining the comparable interference limited service area. These characteristics would include antenna parameters such as front-to-back ratio, and system parameters such as tuner/decoder rejection capability.

3.5.4.2 *Allotment/assignment plan*

These general principles form the basis upon which to develop an allotment plan for an HDTV service. The objective is to provide an HDTV service with coverage areas equivalent to existing NTSC stations.

Selection is accomplished through the use of optimization algorithms which search for combinations of channels in the most congested areas to find available spectrum.

3.5.5 *NTSC taboo interference mechanisms*

3.5.5.1 *Geographic separation for intermodulation (Channels n ± 2, ± 3, ± 4, ± 5) = 32.2 km*

Intermodulation interference results from a combination of input signals such that their sums and differences produce spurious frequency products falling within an eleven channel spread. For that reason, Commission rules for NTSC preclude the near location of stations separated by two, three, four or five channels (the first adjacent channel is precluded also but under a more restrictive separation requirement).

3.5.5.2 *Geographic separation for cross modulation (Channels n ± 2, ± 3, ± 4, ± 5) = 32.2 km*

Cross modulation interference involves the same group of channels as intermodulation but the mechanism is different. In cross modulation interference, the modulation of the undesired channel is superimposed on the modulation of the desired channel. The first evidence of such interference usually comes from vertical and horizontal boundaries of the undesired channel showing in the desired channel.

3.5.5.3 *Geographic separation for the local oscillator (Channel n + 7) = 95.7 km*

The local oscillator of a television receiver is tuned to a frequency falling into the seventh channel above the desired channel in order to produce beats falling into the intermediate frequency (IF) band running from 41 to 47 MHz. That local oscillator can be considered to be a low power transmitter. In older receivers, sufficient energy from the local oscillator leaked out through the tuner to the antenna that interference could be caused to a nearby receiver tuned to the seventh channel. Therefore, the FCC had limited use of the seventh channel to stations separated by at least 95.7 kms (59.5 miles). Modern receivers leak very little of the local oscillator output to the receiving antenna so the general consensus is that the oscillator taboo no longer serves a useful purpose.

3.5.5.4 *Geographic separation for the IF beat (Channels n ± 7, ± 8) = 32.2 km*

When two strong signals are separated by the IF universally employed for NTSC receivers (41-47 MHz), the possibility exists that they will beat against each other and produce an interfering signal in the IF amplifier section of the receiver. The range of signals producing this phenomenon falls in the situations where stations are removed in frequency by 7 or 8 channels.

3.5.5.5 *Geographic separation for half-IF (Channel n + 4) = 32.2 km*

Signals falling in the fourth channel above the desired channel have the potential of beating with the local oscillator tuned to the desired channel to produce a half-IF signal. In the non-linear circuit of the receiver's first detector, the second harmonic of that half-IF signal can be generated and cause interference to the desired channel.

3.5.5.6 *Geographic separation for image (Channel n + 14) = 95.7 km (Channel n + 15) = 119.9 km*

The local oscillator of a television receiver is tuned to a frequency approximately 47 MHz above the lower edge of the desired channel. When that local oscillator frequency and the desired channel signal encounter the first detector of the receiver, the difference beat falls into the 41-47 MHz IF channel. However, an undesired signal above the oscillator frequency will also produce a signal falling within the receiver's IF pass band. For the visual carrier, the critical channel is fifteen above the desired channel. For the aural carrier, the fourteenth channel above the desired channel is critical.

3.6 *Comparison of proposed systems*

3.6.1 *Testing terrestrial digital HDTV systems*

To assist the FCC, the United States of America's television broadcasting industry originally organized the Advanced Television Test Center (ATTC) during 1988 and was joined in 1989 by the television receiver manufacturing industry. The ATTC is a private sector, non-profit organization created to undertake full, fair and impartial testing of the various ATV systems that have been proposed as the United States of America's terrestrial broadcast standard.

On a parallel track, the cable television industry in the United States of America was organizing its own broad research and development activity, and in 1988 it created Cable Television Laboratories (CableLabs). While the broadcasting and cable TV industries had discussed a common venture to evaluate the proposed systems before the ATTC and CableLabs were organized, what has come about, in fact, is a joint testing effort bringing together the resources of the ATTC and CableLabs. The ATTC operates a state-of-art laboratory testing facility in Alexandria, Virginia capable of thoroughly evaluating the proposed systems in a terrestrial broadcast environment. At the same site, CableLabs operates a state-of-the-art laboratory testing facility capable of thoroughly evaluating the proposed systems when transmitted by cable TV including both coaxial cable and fibre-optic transmission.

During the same period, the Canadian industry jointly with the Canadian Government, have established a complementary facility in Ottawa to test all the systems proposed in a well calibrated subjective test environment. All the subjective tests involving average viewers will be conducted in Ottawa at the Advanced Television Evaluation Laboratory (ATEL). ATEL was established within the Communications Research Centre (CRC) division of the Canadian Government's Department of Communications.

Presently there are four digital systems scheduled for test by the ATTC, CableLabs and ATEL. The systems and their scheduled test dates are shown in Table 2. Both objective and subjective tests of all systems will be conducted.

TABLE 2

Proposed digital HDTV television transmission systems before the FCC Advisory Committee*

System name and proponent(s) (in order of testing sequence)	Scheduled test dates (1)
1. DigiCipher General Instrument Corporation/ATVA (2)	14 November 1991 to 7 January 1992
2. DSC-HDTV: digital spectrum compatible HDTV Zenith Electronics Corporation/AT&T	14 January 1992 to 2 March 1992
3. ADTV: advanced digital television North American Philips/ATRC (3)	9 March 1992 to 22 April 1992
4. ATVA-Progressive Massachusetts Institute of Technology/ATVA (2)	29 April 1992 to 15 June 1992

* From data provided by proponents to ATTC.

(1) Official schedule dated 7 June 1991.

(2) American Television Alliance (General Instrument, Massachusetts Institute of Technology).

(3) Advanced Television Research Consortium (NBC, North American Philips, David Sarnoff Research Center, Thomson Consumer Electronics).

The objective and subjective tests are designed to address several key challenges posed in both broadcast and cable transmission:

- planned use of standard 6 MHz channels for transporting vastly increased image content in an advanced television service;
- system robustness in the face of interference and other transmission impairments; and
- the ability of the system to coexist with today's NTSC television service.

Given the importance of comparative evaluation, a common test plan will be applied to all, with individual "system-specific" tests expected to address the individual peculiarities of each system. The ATTC and CableLabs will undertake technical objective assessments of the nature and performance of each system through a simulated broadcast or cable transmission environment, respectively. Using "expert observers", that is, trained television engineers and other analysts, the range over which each system first appears affected by a particular transmission impairment and finally collapses or becomes unwatchable will be established. The resulting output signals over this range for each system will be recorded on digital video tape and the tapes will be sent to ATEL in Canada. These video tapes will be used for subjective evaluation in Canada by "non-expert viewers" – both Canadian and American – of each system's performance over the established range. Traditional techniques, as devised and used through the CCIR, and other extrapolated procedures, plus a few new ones, form the basis of the plan for this important subjective evaluation.

Both objective and subjective analysis of the audio elements of each system will also be undertaken, and is to be managed by the ATTC.

Together the technical objective results from the work in Alexandria and the subjective evaluations from the work in Ottawa will be combined to represent the laboratories' test report on each system. In fact, the work in Canada will be under way reviewing tapes from the first system tested in Alexandria, even as the second system arrives and starts its testing in Alexandria. This parallel evaluation process, reflecting test procedures and methodologies devised and vetted in both the United States of America and Canada, represents an extraordinary joint venture. It means both time and cost savings to the many standards analysts involved and to the system proponents as well. It is intended to provide a "snapshot-in-time" comparison of actual television transmission systems, operating in real time, fully implemented in hardware and to provide the best possible understanding of the options for a practical standard.

Some field testing is also anticipated in this calendar. While the planning for this is now under way in the ACATS, it is expected to be launched as soon as possible with the system or systems which prove in the laboratory to warrant field trials. Such final proof in the "real world" must be established before a new standard could be reasonably confirmed and implemented.

The subjective evaluations will address two important issues: first, whether average, "non-expert" viewers perceive various interference conditions and other impairments as objectionable, tolerable, or at all, and at the same levels as "expert" viewers do; and second, how average viewers rate the inherent quality of a given system's pictures against the best-quality reference image. Fourteen static images, derived from photographs, and eighteen dynamic scenes, drawn from video and film sources, will provide the test materials for these subjective evaluations. Each scene, both still and motion, was designed by a group of specialists working in the ACATS. Strongly guided by its psychophysicist participants, the group designed special test materials not unlike "typical" television scenes, but also appropriate to help isolate the particular element to be studied in the test using that scene, for example, resolution, motion rendition, related luminance and chrominance performance, etc.

The static images were each transferred into the four different scanning formats required by the systems to be tested using a specially modified commercial digital image processing system. The motion sequences derived from video sources have been produced in keeping with the ACATS' requirements, with each scene shot in each of the four scanning formats, as specified by the proponents, plus NTSC. Since there are no digital video tape recorders available for the 1 050-line interlaced and 787.5-line progressive formats, a solution had to be found to record the signals so as to ensure a "level playing field" for test materials for all proponents. This has been made technically possible through the use of a format converter that converts the analogue camera output of each of these scanning formats into digital form and then re-arranges the resulting data so as to permit it to be recorded on a commercially available 1 125-line high-definition digital video tape recorder. The resulting tapes are played back through the format converter and the scenes are restored to their original format – a transparent process which permits all test materials to be "identical" and repeatable. The use of the format converter also allows all of the test results to be recorded for archival purposes and allows the use of pre-recorded tapes for the subjective testing rather than relying on live-action cameras and continuously functioning proponent hardware.

The challenging procedure for shooting the video material, which required careful matching of action, lighting, and angles to ensure "identical" test materials in each required format was accomplished under the overall guidance of a specialist group within the ACATS. The video work itself was done by a major New York studio under the supervision of the head of ATEL which, in turn, will conduct the subjective tests using these materials.

3.6.2 *Parameter values of proposed digital HDTV terrestrial broadcasting systems*

Over the past twelve months, the identity of the advanced television proponents and their system designs has changed considerably in the United States of America. The first all-digital HDTV system was proposed in June 1990, followed by the replacement of three of the previously proposed hybrid systems with all-digital designs. All of the all-digital proponents claim that their systems can provide true HDTV picture quality throughout a station's service area. It is promised that all-digital approaches will be more flexible, provide better bandwidth compression, permit noise-free tape recording in the studio and the home, have no noise, interference, or ghost accumulation from cascaded processing and/or cascaded transmission segments, and provide synergy with other communications and computer equipment. The performance and features of a system are dependent on the system design philosophies. For example, some proposed systems emphasize picture resolution while others emphasize robust transmission. Under a fixed total data rate, data allocation is a trade-off issue.

A table of attributes, characteristics and processes of digital HDTV terrestrial broadcasting systems is provided here to compare the proposed digital systems. All of the data collected in Table 3 are based on the technical descriptions submitted by the proponents to the United States Federal Communications Commission Advisory Committee on Advanced Television Service. A blank space indicates that the information was not available from documents. The data provided here are subject to change because these proposed systems are still being optimized.

3.7 *Harmonization*

Digital HDTV systems have the potential for facilitating interoperability among high resolution image systems. Selection of an advanced television system that incorporates attributes needed for interoperability will harmonize interchange of still and moving images from diverse sources.

3.7.1 *Benefits of interoperability*

The future benefits of video and other image technologies will be greatly enhanced if universal interchange of all kinds of images and image sequences can be implemented and managed economically. The ultimate beneficiary is the consumer who will have, at the consumer's option, image information of any kind in a form chosen by the consumer, instantly available, at an affordable price.

Rapid advances in digital semiconductors, digital communications, and digital processing algorithms will make it possible to tailor the video technology to specific applications (in terms of picture quality, price, format, and performance). Such a diversity in the video marketplace will be a positive development only if it is easy to move among different formats, applications, industries, and media. The key idea is to remove impediments to interworking among multiple formats so that market forces can guide the developments of products and services.

3.7.2 *Potential drawbacks of interoperability*

There are economic costs associated with the inclusion of interoperability in a video architecture. For example, building the desired flexibility into a terrestrial broadcast HDTV system could increase the cost of TV receivers. Not only will obvious additional costs be incurred due to additional connectors and interfaces, but the system architecture may need to be made more complex.

TABLE 3

Table of attributes, characteristics, and processes of digital HDTV terrestrial broadcasting systems

	DigiCipher	DSC-HDTV	ADTV	ATVA-P
Lines per frame	1 050	787/788	1 050	787/788
Frames per second	29.97	59.94	29.97	59.94
Interlace	2:1	1:1	2:1	1:1
Horizontal scan rate (kHz)	31.469	47.203	31.469	47.203
Aspect ratio	16:9	16:9	16:9	16:9
Active video pixels	1 408(H) × 960(V) (luminance) 350(H) × 480(V) (chrominance)	1 280(H) × 720(V) (luminance) 640(H) × 360(V) (chrominance)	1 440(H) × 960(V) (luminance) 720(H) × 480(V) (chrominance)	1 280(H) × 720(V)
Pixel aspect ratio	33:40	1:1	27:32	1:1
Bandwidth (MHz)	21.5 (luminance) 5.4 (chrominance)	34 (luminance) 17 (chrominance)	27 (Nyquist limit)	34 (luminance) 34 (chrominance)
Colorimetry	SMPTE 240 M	SMPTE 240 M	SMPTE 240 M	SMPTE 240 M
Video compression algorithm	Motion-compensated DCT coding	Motion-compensated transform coding (DCT and VQ)	Motion-compensated DCT coding (MPEG-based)	Motion-compensated transform/sub-band coding
Block size	8 × 8	8 × 8	8 × 8	8 × 8
Sampling frequency (MHz)	53.65	75.3	54	75.3
Audio bandwidth (kHz)	20	20	20	20
Audio sampling frequency (kHz)	48	47.203	48	48
Dynamic range (dB)	85	96	96	
Number of audio channels	4	4	4	4

TABLE 3 *(continued)*

	DigiCipher	DSC-HDTV	ADTV	ATVA-P
Video data rate (Mbit/s)	12.59 (16-QAM) 17.49 (32-QAM)	Automatically varies from 8.6 to 17.1	14.98 (can be shared with additional audio and/or data)	15.636
Audio data rate (Mbit/s)	0.503	0.5	0.512 (nominal)	0.5
Control data (kbit/s)	126	40 (spare)	40 (data)	126 (access control)
Ancillary data (kbit/s)	126	413	512 (nominal)	126 kbit/s
Synchronization	Not applicable	292 to 544 kbit/s	Not applicable	Not applicable
Total data (Mbit/s)	19.51 (16-QAM) 24.39 (32-QAM)	11.1 to 21.0 Mbit/s	21.00	19.43
Error correction overhead (Mbit/s)	6.17	1.3 to 2.4	23.6% (4.96)	3.042
RF modulation (terrestrial)	16-QAM or 32-QAM	2 level and 4 level VSB	Spectrally shaped QAM	16-QAM
3 dB bandwidth (terrestrial) (MHz)	4.88	5.38	5.2	4.86
C/N threshold (terrestrial) (dB)	12.5 (16-QAM) 16.5 (32-QAM)	16 (4 level data) 10 (2 level data)	16	19
Channel equalization (ghost cancelling) (μs)	–2 to +24 (multiple ghosts)	–2 to +20 (multiple ghosts)	16 (may be extended to 40)	2 (complex multipath) 32 (single long multipath)
RF modulation (satellite)	QPSK	MSK	QPSK	
Bandwidth (satellite) (MHz)	24/2 channels	20/channel	24/2 channels	
C/N threshold (satellite) (dB)	7.5	8	8	

Note 1 – Data subject to change; data provided by the proponents; methods of measurement may vary by system.

3.7.3 *Types of interoperability*

The potential for image interoperability exists at several levels or dimensions: among different signal formats, among different-transport media, among different industries, among different applications, among different epochs, and among different-geopolitical entities.

3.7.4 *Importance of digital representation for interoperability*

Digital representation of signals is the key element in achieving interoperability for images and video. The digital nature of the signal means that all systems that process the signal have identical material to process. The ease of storing, transporting, and processing digital data is matched by the growing speed, power, and economy of semiconductors.

Once in digital form, signals can be filtered and processed in a predictable and reproducible way so that conversions among formats can be implemented using functions selected based on mathematical theories such as sampling, interpolation, and prediction.

3.7.5 *Industries with interests in high-resolution images*

While the traditional entertainment television industry has been built around a single dominant format (NTSC in the United States of America), the non-entertainment industries have generated a number of formats for still and moving images. In some cases the non-entertainment applications have used NTSC, although there has not always been a good match of NTSC capabilities to requirements.

Many now seem to believe that technology has reached a point where many new standards are about to be set, and the opportunity should not be missed to harmonize the various image and video standards. The advocates of harmonization are mainly in the computer, computer graphics, and telecommunications industries, and academia.

The advantage seen by those industries from interoperability is the ability to share a common technology with the large consumer television market thereby increasing the size of the market for non-entertainment image and video applications.

3.7.6 *Specific attributes relevant to interoperability*

Certain specific attributes of image-related systems contribute to interoperability and are described below.

3.7.6.1 *Digital representation*

DigiCipher, DSC-HDTV, ADTV, and ATVA-P use digital processing and digital broadcasting and therefore meet the major requirement for interoperability, digital signal representation.

3.7.6.2 *Progressive scanning*

Progressive scanning in a raster-based sequence of images simplifies, to some extent, the filtering and interpolation used to convert among formats with different numbers of scan lines, different numbers of samples per line, and different temporal sampling (i.e., picture rate). DSC-HDTV and ATVA-P use progressive scanning.

3.7.6.3 *Square pixels*

For computer graphics, equal geometric spacing among horizontal samples on a line and among samples displaced vertically is desirable for simple rendering of objects that may be transformed after creation. DSC-HDTV and ATVA-P use square pixels.

3.7.6.4 *Provision for headers and descriptors within data*

An important area of agreement among advocates of interoperability and harmonization of images and video is the desirability of headers and descriptors imbedded within the stream of image data. The purpose of the headers and descriptors is to identify reliably and unambiguously the form of the data. The headers could include information on how the images or image sequences were originated, processed, and compressed. The headers could use a small fraction of data capacity to make image data streams self-identifying.

DigiCipher, DSC-HDTV, ADTV, and ATVA-P provide for auxiliary data in digital form. Part of that auxiliary data channel capacity could be used for headers and descriptors to make the data streams self-identifying.

3.8. Alternative terrestrial systems

A number of terrestrial distribution systems will be used for the delivery of digital HDTV to the general public. These systems such as cable, MMDS, and optical fibre networks will have their own intrinsic limitations on transmission channel performance. It is important that the system selected be immune to these transmission channel limitations. Some of the tests in the test plan reflect such limitations. Ultimately, the received signal quality should be independent of the delivery medium to the viewer.

4. Conclusions

Digital television terrestrial broadcasting within the constraints of the existing VHF/UHF bands has been shown to be feasible.

A range of possible source coding, channel coding, and modulation techniques is under investigation on a world-wide basis with the expectation that the work could lead to substantial advances in the technology, and increasing proof of performance.