that the change in the characteristics with a change in frequency becomes more severe with increasing trap length l_t, and the bandwidth becomes small, while a short trap length l_t shows a small change and a tendency for the bandwidth to become wide. For $l_t = 0$, a wide bandwidth for pattern and gain was obtained for the 2L type. The input impedance has a value very close to 50 Ω, essentially the same as the characteristic impedance of the feed cable over a very wide frequency range. Thus, a satisfactory explanation was given with regard to the matching conditions. Popular television antennas cover the properties of many basic types of antennas which are the mainstream of antenna technology. It has been

TELEVISION BROADCAST TRANSMISSION STANDARDS

Since the invention of television, the images and sound have been captured, processed, transmitted, received, and displayed using analog technology, where the picture and sound elements are represented by signals that are proportional to the image amplitude and sound volume.

In more recent years, as solid-state technology has developed, spurred primarily by the development of computers, digital technology has gradually been introduced into the handling of the television signal, both for image and sound. The digital electric signal representing the various elements of the image and sound is composed of binary numbers that represent the image intensity, color, and so on, and the sound characteristics.

Many portions of television systems are now hybrid combinations of analog and digital, and it is expected that eventually all television equipment will be fully digital, except for the transducers, cameras, and microphones (whose inputs are analog) and the television displays and loudspeakers (whose outputs are analog).

The currently used broadcast television transmission standards [National Television Systems Committee (NTSC), phase alternate line (PAL), and sequential and memory (SECAM)] for 525- and 625-line systems were designed around analog technology; and although significant portions of those broadcast systems are now hybrid analog/digital or digital, the “over the air” transmission system is still analog. Furthermore, other than for “component” processed portions of the system, the video signals take the same “encoded” form from studio camera to receiver and conform to the same standard.

The recently developed ATSC Digital Television Standard, however, uses digital technology for "over the air" transmission, and the digital signals used from the studio camera to the receiver, while they represent the same image and sound, differ in form in portions of the transmission system. This variation is such that in the studio, maximum image and sound information is coded digitally; but during recording, special effects processing, distribution around a broadcast facility, and transmission, the digital signal is "compressed" to an increasing extent as it approaches its final destination at the home. This permits practical and economical handling of the signal.

ANALOG TELEVISION SYSTEMS

Black-and-White Television

It is the purpose of all conventional broadcast television systems to provide instantaneous vision beyond human sight, a window into which the viewer may peer to see activity at another place. Not surprisingly, all of the modern systems evolved to have similar characteristics. Basically, a sampling structure is used to convert a three-dimensional image (horizontal, vertical, and temporal variations) into a continuous time-varying broadband electrical signal. This modulates a high-frequency carrier with the accompanying sound, and it is broadcast over the airwaves. Reasonably inexpensive consumer television sets are capable of recovering the picture and sound in the viewer's home.

Image Representation. The sampling structure first divides the motion into a series of still pictures to be sequenced rapidly enough to restore an illusion of movement. Next, each individual picture is divided vertically into sufficient segments so that enough definition can be retrieved in this dimension at the receiver. This process is called *scanning.* The individual pictures generated are known as *frames,* each of which contains *scanning lines* from top to bottom.

The number of scanning lines necessary was derived from typical room dimensions and practical display size. Based on the acuity of human vision, a viewing distance of four to six picture heights is intended. The scanning lines must be capable of enough transitions to resolve comparable definition horizontally. The image *aspect ratio* (width/height) of all conventional systems is 4 : 3, from the motion picture industry "academy aperture." All systems sample the picture from the top left to bottom right.

In professional cinema, the projection rate of 48 Hz is sufficient to make flicker practically invisible. Long-distance electric power distribution networks throughout the world use slightly higher rates of 50 Hz to 60 Hz alternating current. To minimize the movement of vertical "hum" in the picture caused by marginal filtering in direct current power supplies, the picture repetition rate was made to equal the power line frequency.

A variation of this process used by all conventional systems is *interlaced scanning,* whereby every other line is scanned to produce a picture with half the vertical resolution, known as a *field.* The following field "fills in" the missing lines to form the complete frame. Each field illuminates a sufficient portion of the display so that flicker is practically invisible, yet only half the information is being generated. This conserves bandwidth in transmission. For both fields to start and stop at the same point vertically, one field must have a half scanning line at the top, and the other field must have a half scanning line at the bottom of the picture. This results in an odd number of scanning lines for the entire frame.

Mechanical systems using rotating disks with spiral holes to scan the image were investigated in the 1920s and 1930s, but these efforts gave way to "all electronic" television. Prior to World War II, developers in the United States experimented with 343-line and 441-line systems. Developers in Great Britain began a 405-line service, and after the war, the French developed an 819-line system, but these are no longer in use.

Synchronization. In most of North and South America and the Far East, where the power line frequency is 60 Hz, a 525-line system became the norm. This results in an interlaced scanning line rate of 15.750 kHz. The development of color television in Europe led to standardization of 625 lines in much of the rest of the world. The resulting line frequency with a 50 Hz field rate is 15.625 kHz. The similar line and field rates enable the use of similar picture tube deflection circuitry and components. Horizontal and vertical frequencies must be synchronous and phase-locked, so they are derived from a common oscillator.

Synchronization pulses are inserted between each scanning line (Fig. 1) and between each field to enable the television receiver to present the picture details with the same spatial orientation as that of the camera. The *sync* pulses are of opposite polarity from the picture information, permitting easy differentiation in the receiver. The line sync pulses, occurring at a faster rate, are narrower than the field sync pulses, which typically are the duration of several lines. Sync separation circuitry in the receiver discriminates between the two time constants. Sync pulses cause the scanning to rapidly *retrace* from right to left and from bottom to top.

Blanking. To provide time for the scanning circuits to reposition and stabilize at the start of a line or field, the picture signal is *blanked,* or turned off. This occurs just before (front porch) and for a short time after (back porch) the horizontal sync pulse, as well as for several lines before and after vertical sync. During vertical sync, *serrations* are inserted to maintain horizontal synchronization. Shorter *equalizing pulses* are added in the several blanked lines before and after vertical sync (Fig. 2). All these pulses occur at twice the rate of normal sync pulses so that the vertical interval of both fields (which are offset by one-half line) can be identical, simplifying circuit design.

Additional scanning lines are blanked before the active picture begins; typically there is a total of 25 blanked lines per field in 625-line systems and 21 blanked lines per field for the 525-line system M. Modern television receivers complete the vertical retrace very soon after the vertical sync pulse is received. The extra blanked lines now contain various ancillary signals, such as for short-time and line-time distortion and noise measurement, ghost cancellation, source identification, closed captioning, and teletext.

Fields and lines of each frame are numbered for technical convenience. In the 625-line systems, field 1 is that which be-

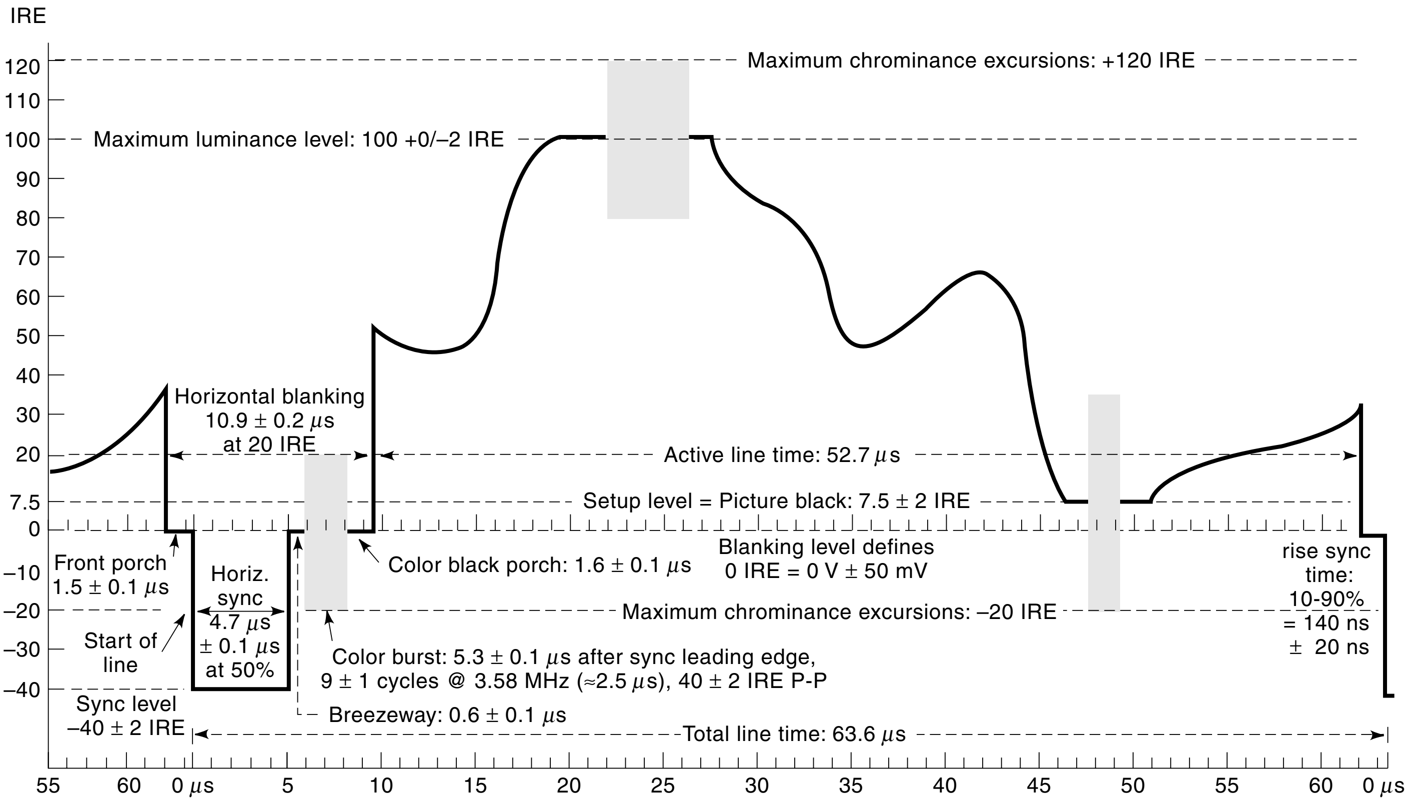


Figure 1. 525-line system M: Line-time signal specifications.

gins the active picture with a half line of video. In the 525-line system M, the active picture of field 1 begins with a full line of video. Lines are numbered sequentially throughout the frame, beginning at the vertical sync pulse in the 625-line systems. For the 525-line system M, the line numbering begins at the first complete line of blanking for each field. Field 1 continues halfway through line 263, and then field 2 continues through line 262.

Signal Levels. During blanking, the video signal is at 0 V, the reference used to measure picture (positive-going) and sync (negative-going) levels. Signal amplitudes are measured directly in millivolts, except, because of changes made during the conversion to color, the 525-line system uses *IRE units.* A specialized oscilloscope is used to monitor characteristics of the signal amplitude and period. The *waveform monitor* has its voltage scale calibrated in millivolts (or IRE units for 525-line applications), and its time base is calibrated to scanning line and picture field rates, as well as in microseconds (Fig. 3).

Originally, the 525-line system used an amplitude of 1 V peak-to-peak (p-p) for the picture information, and it used 0.4 V for sync. So that color information (modulated onto a *subcarrier* which can extend above peak white level) could be accommodated within the same dynamic range of existing equipment, the 1.4 V p-p scaling was compressed in amplitude to 1 V p-p. This created fractional voltage levels for peak white (714.3 mV) and sync (−286.7 mV), so a 1 V scale of 140 IRE units was adopted to simplify measurement. The 625-line standards did not have this historical complication. The peak white level is 700 mV, and sync level is −300 mV.

Another anachronism of the 525-line system is the use of a direct-current (dc) offset of the picture black from blanking level. This was done to ensure that during retrace, the electron beam in the display tube was completely cut off, so *retrace lines* did not appear in the picture. This *setup level* originally varied between 5 and 10 IRE units above blanking, but was standardized at 7.5 IRE for color TV, although it has been discarded altogether in Japan. Setup, or "lift," was used to some extent in earlier systems, but abandoned by the advent of 625-line services.

The electrical-to-optical transfer characteristic (*gamma*) of the cathode-ray picture tube is nonlinear. Doubling the video signal level applied to the control grid of the picture tube does not cause the light output to double, rather, it follows a power law of approximately 2.5. To correct for this, the video signal itself is made nonlinear, with an opposite transfer characteristic of about 0.4. This correction is applied at the camera in all systems.

Resolution. Resolution in the vertical direction is determined by taking the total number of scanning lines and subtracting those used for vertical blanking. This is multiplied by 0.7, the *Kell factor,* a correction for slight overlap between adjacent lines and the effect of imperfect interlace. By convention, television resolution is expressed in *television* (*TV*) *lines per picture height,* in contrast to photographic "line pairs per millimeter." Since the resolution is fixed by the scanning system, picture size is immaterial. Note that a vertical "line pair" in television requires two scanning lines.

To compute the bandwidth necessary for equal horizontal resolution, the vertical resolution is multiplied by the aspect

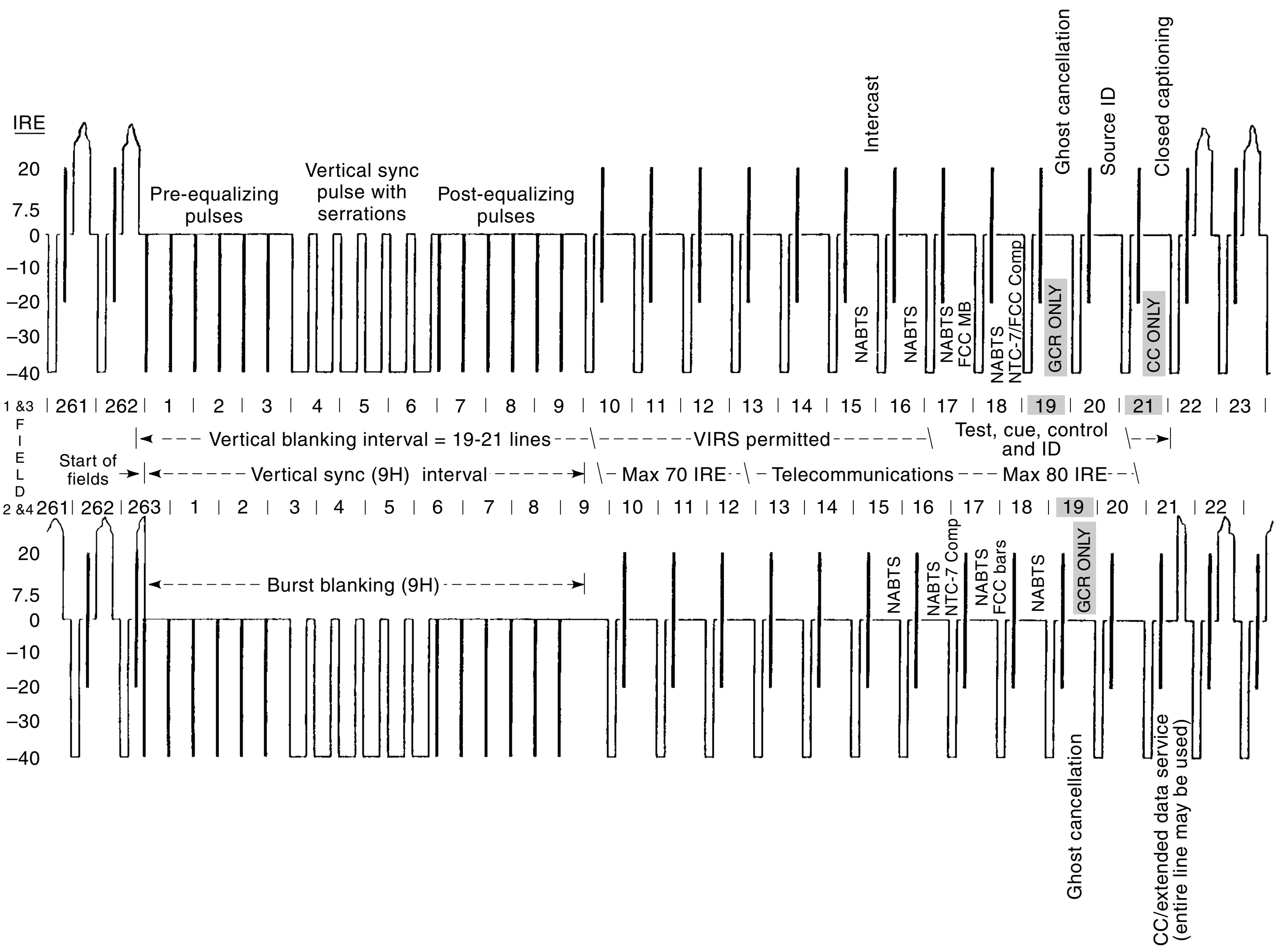


Figure 2. 525-line system M: field-time and vertical interval signal specifications.

ratio of 4/3 and is divided by the ratio of total scanning line time to active picture (unblanked) line time. This number is halved because an electric cycle defines a line pair, whereas a "TV line of resolution" is really only one transition. Multiplying the number of cycles per scanning line by the total number of scanning lines in a field, and then multiplying the number of fields per second, gives the bandwidth of the baseband video signal.

Broadcasting Standards. The various systems have been assigned letter designations by the International Telecommunications Union (ITU). The letters were assigned as the systems were registered, so alphabetical order bears no relation to system differences (Table 1), but a rearrangement highlights similarities (Table 2). Only scanning parameters and radio-frequency (RF) characteristics are defined; color encoding is not specified. Systems A, C, E, and F are no longer used.

Portions of the very-high-frequency (VHF) and ultrahigh-frequency (UHF) RF spectrum are divided into *channels* for television broadcast. Modern channel assignments are 6 MHz wide in the Americas and the Far East. Elsewhere, they are generally 7 MHz in VHF and 8 MHz in UHF, with the carrier a fixed distance from one edge. Since, in most systems, the picture carrier is near the lower edge and the audio signals are at the upper end, when the opposite is true, the channels are called *inverted.*

As a bandwidth-saving technique, the amplitude-modulated RF signal is filtered so that only one sideband is fully emitted; the other sideband is *vestigial,* or partially suppressed, which aids in fine tuning to the correct carrier frequency at the receiver. The full sideband, which represents the video bandwidth, extends in the direction of the audio carrier(s), but sufficient guard band is included to prevent interference.

Bandwidth of the vestigial sideband varies among systems as does the placement of the audio carrier in relation to the picture carrier (Fig. 4). These factors complicate receiver design in areas where signals of two or more systems may exist. The main audio signal is sent via an amplitude-modulated or, more commonly, frequency-modulated carrier. Peak deviation in frequency modulation (FM) is ±50 kHz, with 50 μs preemphasis, except ±25 kHz and 75 μs for systems M and N. Pre-

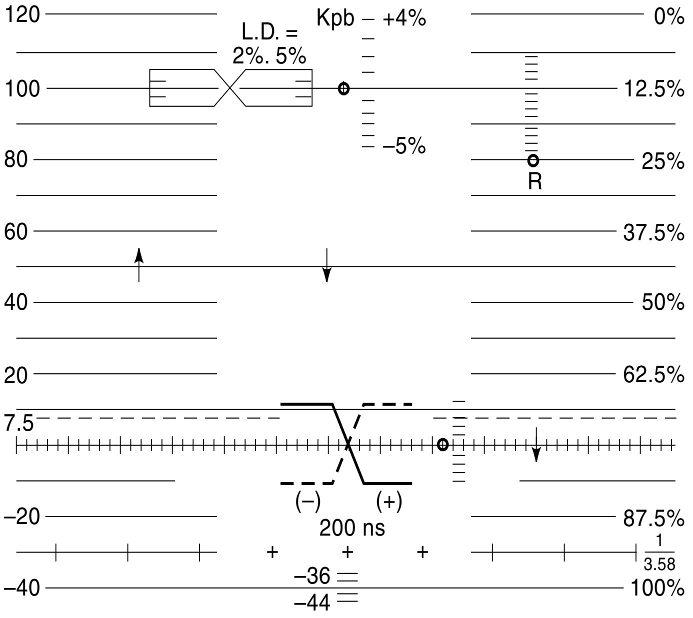


Figure 3. Typical NTSC-M waveform monitor graticule. A number of additional markings are for measurement of various signal distortions.

emphasis for improving the signal-to-noise ratio is common in FM systems; its use in some amplitude-modulation (AM) systems was to simplify receivers which could accommodate both modulation schemes.

Amplitude modulation is used in all systems for the video waveform, which, unlike audio, is not sinusoidal. The majority of systems employ a *negative sense of modulation,* such that negative excursions of the baseband signal produce an increase in the amplitude of the modulated carrier. This allows the constant amplitude sync pulses to serve as an indication of the received RF signal level for automatic gain control. Also, interfering electric energy tends to produce less noticeable black flashes in the received picture, and the duty cycle of the signal is reduced, which consumes less power at the transmitter.

Multichannel Sound

Early attempts to provide stereo sound for special TV events involved *simulcasting,* whereby an FM radio station in the same coverage area broadcast the stereo audio for the program. Due to the high profitability of FM radio today, this scheme is becoming impractical. For the 525-line system M, with channels of only 6 MHz bandwidth, a multiplexing scheme is used on the existing single audio carrier. Due to the wider channel bandwidths in 625-line systems, multiple sound carriers emerged as the solution.

Multiplex Sound Systems. In the United States, Zenith Electronics developed multichannel television sound (MTS), a pilot-tone system in which the sum of the two stereo channels (L + R) modulates the main TV audio FM carrier, providing a monophonic signal to conventional receivers. A difference signal (L − R) is dbx-TV suppressed-carrier amplitude-modulated onto an audio subcarrier at twice the line scanning frequency ($2f_{\mathrm{H}}$), while a pilot is sent at the line frequency as a reference for demodulation. A second audio program (SAP) may be frequency modulated at $5f_{\mathrm{H}}$, and nonpublic voice or data may be included at $6.5f_{\mathrm{H}}$.

Japan's NHK developed a similar *FM/FM* stereo system using FM of the L − R subchannel at $2f_{\mathrm{H}}$. A control subcarrier at $3.5f_{\mathrm{H}}$ is tone-modulated to indicate whether stereo or second audio programming is being broadcast.

Multiple Carrier Systems. In Germany, IRT introduced *Zweiton,* a dual carrier system for transmission standards B and G. In both standards, the main carrier is frequency-modulated at 5.5 MHz above the vision carrier. For stereo, this carrier conveys the sum of the two channels (L + R). The second frequency-modulated sound carrier is placed 15.5 times the line scanning frequency above the main carrier, or 5.742 MHz above the vision carrier. For transmission system D, a similar relationship exists to the 6.0 MHz main channel. For stereo, this carrier conveys the right audio channel only.

A reference carrier at $3f_{\mathrm{H}}$ is tone-modulated, and the particular tone frequency switches receivers for stereo or second audio channel sound. A variant is used in Korea where the second carrier is placed at 4.72 MHz above the vision carrier and conveys L − R information.

The British Broadcasting Corporation (BBC) in Britain developed near-instantaneous companded audio multiplex (NICAM), a digital sound carrier system. Both audio channels are sampled at 32 kHz with 14-bit resolution. Each sample is compressed to 10 bits, then arranged into frame packages of 728-bit length. These are rearranged and then the data are scrambled to disperse the effect of noise at the receiver. Finally, two bits at a time are fed to a QPSK modulator for transmission.

Either stereo or two independent sound signals may be transmitted. Other possible combinations are (1) one sound and one data channel or (2) two data channels. The original analog-modulated single-channel sound carrier is retained for older receivers. The digital carrier is 6.552 MHz above the vision carrier for transmission system I, or 5.85 MHz for systems B, G, and L.

NTSC Color Television

It has long been recognized that color vision in humans results from three types of photoreceptors in the eye, each sensitive to a different portion of the visible spectrum. The ratio of excitation creates the perception of hue and saturation, while the aggregate evokes the sensation of brightness. Stimulating the three types of photoreceptors using three wavelengths of light can produce the impression of a wide gamut of colors. For television, the image is optically divided into three primary color images, and this information is delivered to the receiver, which spatially integrates the three pictures, something like tripack color film and printing.

Sequential Color Systems. The first attempts at commercial color TV involved transmitting the three color images in a *sequential* fashion. Compatibility with existing transmitters was essential from an economic standpoint. Because line-sequential transmission caused crawl patterning, field-sequen-

Table 1. Principal Characteristics of World Television Systems

Standard	A	B/G	C	D/K	E	F	H	I	K′	L	L′	M	N
	United Kingdom	Western Europe	Luxembourg	Eastern Europe	France	Belgium		United Kingdom	French Overseas Territories	France		North America/ Far East	South America
Frequency band	VHF	V/U	VHF	V/U	VHF	VHF	UHF	V/U	V/U	V-3/U	VHF-1	V/U	V/U
Channel B/W (MHz)	5	7/8	7	8	14	7	8	8	8	8	8	6	6
Visual/Edge separation (MHz)	−1.25	+1.25	+1.25	+1.25	±2.83	+1.25	+1.25	+1.25	+1.25	+1.25	−1.25	+1.25	+1.25
Video B/W (MHz)	3	5	5	6	10	5	5	5.5	6	6	6	4.2	4.2
Vestigial sideband (MHz)	+0.75	−0.75	−0.75	−0.75	±2.0	−0.75	−1.25	−1.25	−1.25	−1.25	+1.25	−0.75	−0.75
Visual modulation polarity (Wht=)	Pos.	Neg.	Pos.	Neg.	Pos.	Pos.	Neg.	Neg.	Neg.	Pos.	Pos.	Neg.	Neg.
Picture/synchronization ratio	7/3	7/3	7/3	7/3	7/3	7/3	7/3	7/3	7/3	7/3	7/3	10/4	7/3
Black pedestal (%)	0	0	0	0	0	0	0	0	0	0	0	7.5	0
Visual/aural separation (MHz)	−3.5	+5.5	+5.5	+6.5	±11.15	+5.5	+5.5	+6.0	+6.5	+6.5	−6.5	+4.5	+4.5
Aural modulation	AM	FM	AM	FM	AM	AM	FM	FM	FM	AM	AM	FM	FM
Aural peak Deviation (kHz)		±50		±50			±50	±50	±50			±25	±25
Aural preemphasis (μs)		50	50	50		50	50	50	50			75	75
Lines per frame	405	625	625	625	819	819	625	625	625	625	625	525	625
Field blanking (lines)	13	25	25	25	33	33	25	25	25	25	25	21	25
Field synchronization (lines)	4	2.5	2.5	2.5	20μs	3.5	2.5	2.5	2.5	2.5	2.5	3	2.5
Equalization pulses (lines)	0	2.5	2.5	2.5	0	3.5	2.5	2.5	2.5	2.5	2.5	3	2.5
Vertical resolution (L/ph)	254	413	413	413	516	516	413	413	413	413	413	350	413
Horizontal resolution (L/ph)	270	400	400	450	635	400	400	430	450	450	450	320	320
Field rate (Hz)	50	50	50	50	50	50	50	50	50	50	50	59.94	50
Line rate (Hz)	10,125	15,625	15,625	15,625	20,475	20,475	15,625	15,625	15,625	15,625	15,625	15,734	15,625
Line blanking (μs)	18	12	12	12	9.5	9.2	12	12	12	12	12	10.9	12
Front porch (μs)	1.75	1.5	1.4	1.5	0.6	1.1	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Line synchronization (μs)	9.0	4.7	5.0	4.7	2.5	3.6	4.7	4.7	4.7	4.7	4.7	4.7	4.7

tial was preferred. However, there was no separate *luminance* signal for existing black-and-white receivers to use.

To reduce flicker caused by the apparent brightness difference between the three primary colors, the field rate had to be increased, and maintaining an equivalent channel bandwidth required the number of scanning lines to be reduced. These changes aggravated the compatibility problem with existing sets. A field-sequential system developed by the Columbia Broadcasting System (CBS) network was briefly commissioned in the United States during 1951.

To be *compatible,* a color television system must have the same channel bandwidth as existing monochrome transmitters and receivers, use equivalent scanning parameters, and supply the same luminance signal, as if the picture were black and white. An all-industry body, the National Television Systems Committee (NTSC), was set up in the United States to devise such a color TV system.

Separate Luminance and Mixed Highs. The human visual system senses shapes and edges from brightness variations. Color only fills in the larger areas, much like a child's coloring book. At the suggestion of Hazeltine Electronics, the existing wide-bandwidth luminance signal of black-and-white television was retained. The color information is limited to a much narrower bandwidth, on the order of 1 MHz, restricting its resolution in the horizontal direction.

This first led to a dot-sequential system which sampled the three colors many times along each scanning line to form a high-frequency chrominance signal. The frequency of sampling may be likened to a *subcarrier* signal whose amplitude and phase are changing according to color variations along the line. At the receiver, the "dot" patterns of each primary resulting from sampling are averaged in low-pass frequency filters. The result is a continuous but low-resolution full-color signal. Equal amounts of their higher-frequency components

Table 2. Survey of World Television Systems

			Bandwidth										
Standard	Field	Lines	Channel	Video	Vestigial Sideband	Polarity	Audio	Standard	VHF	UHF	NTSC	PAL	SECAM
M	60	525	6	4.2	−0.75	Neg.	FM	M	√	√	√	√	
N	50	625						N	√	√		√	
D			8	6.0				D	√			√	√
K								K		√			√
L'					+1.25	Pos.	AM	L'	√				√
L					−1.25			L	√	√			√
K'						Neg.	FM	K'	√				√
I				5.5				I	√	√		√	
H				5.0				H		√		√	
G					−0.75			G		√		√	√
B			7					B	√			√	√
C						Pos.	AM	C	√	Obsolete Standards			
F		819						F	√				
E			14	10.0	±2.0			E	√				
A		405	5	3.0	+0.75			A	√				

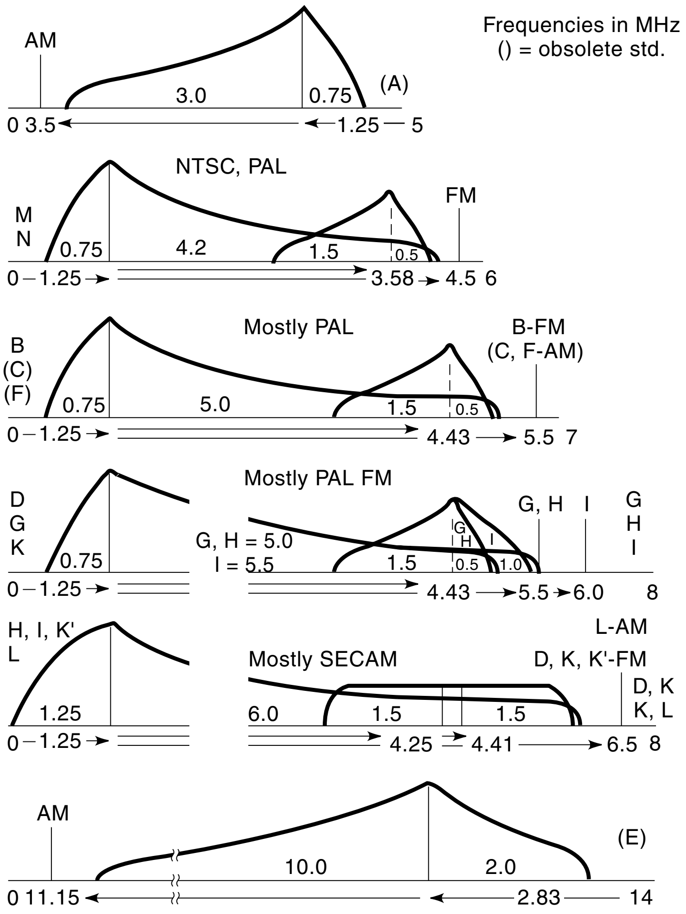


Figure 4. Television RF channel spectra for the various world television systems. For simplicity, only a single illustration of the lower and upper portions of the channel spectra is shown for the 8 MHz wide channels. Therefore, for systems D, H, I, and K, the lower and upper illustrations are not adjacent to each other.

are summed to form a *mixed-highs* signal for fine luminance detail ($Y = \frac{1}{3}R + \frac{1}{3}G + \frac{1}{3}B$), an idea from Philco.

Quadrature Modulation. The dot-sequential concept formed the basis for a more sophisticated simultaneous system. The luminance signal contains both high- and low-frequency components. Only two lower-resolution color signals are needed (the third can be derived by subtracting their sum from the low-frequency portion of luminance). The spectral composition of green is nearest to that of luminance, so transmitting the red and blue signals improves the signal-to-noise performance. These low-frequency color signals are sampled using a time-multiplexing technique proposed by Philco, known as *quadrature modulation.*

The chrominance signal is formed by the addition of two subcarriers, which are locked at the same frequency but differ in phase by 90°. The two subcarriers are modulated by separate baseband signals such that each is sampled when the other carrier is at a null. This results in the subcarrier being modulated in both amplitude and phase. The amplitude relates to the saturation of the color, while the phase component corresponds to the hue (Fig. 5).

Frequency Multiplexing. The sampling rate is more than twice the highest frequency of the color signals after low-pass filtering, so the chrominance information shares the upper part of the video spectrum with luminance. This frequency-multiplexing scheme was put forward by General Electric. The scanning process involves sampling the image at line and field rates; therefore, energy in the video signal is concentrated at intervals of the line and field frequencies. These *sidebands* leave pockets between them where very little energy exists.

The exact subcarrier frequency was made an odd multiple of one-half the line scanning frequency. This causes sidebands containing the color information to likewise fall in between those of the existing luminance signal (Fig. 6). Therefore, the phase of the subcarrier signal is opposite line-to-line. This prevents the positive and negative excursions of subcarrier

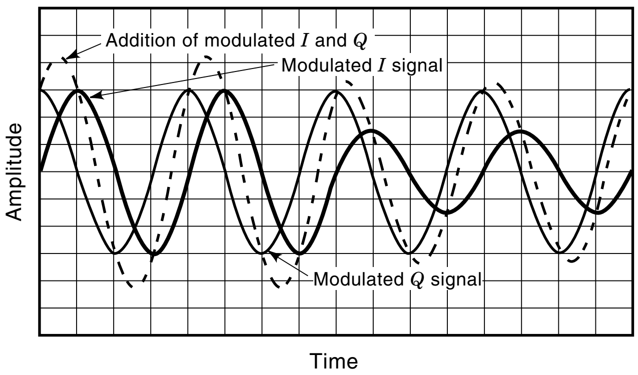


Figure 5. Quadrature modulation. Addition of two amplitude-modulated signals whose carrier frequencies are in phase quadrature (same frequency but offset in phase by 90°) produces an output signal whose carrier is modulated in both amplitude (AM) and phase (PM) simultaneously. This method of combining two baseband signals onto a single carrier is called quadrature modulation. In the case of NTSC or PAL encoding for color television, the two baseband components represent the two chrominance signals (I and Q for NTSC, U and V for PAL). The resulting amplitude of the subcarrier relates to the saturation, while the phase conveys the hue information. The frequency of the subcarrier is unchanged.

from lining up vertically in the picture, and it results in a less objectionable "dot" interference pattern between the subcarrier and luminance signal. Comb filtering to separate luminance and chrominance may be employed by examining the phase of information around the subcarrier frequency on adjacent lines. The dot pattern is further concealed since the subcarrier phase is also opposite frame-to-frame.

A *four-field sequence* is established whereby the two interlaced picture fields, together with the alternating phase of subcarrier on sequential frames, requires the proper sequence to be maintained. Sources to be intercut or mixed must be properly timed, and editing points must be chosen to preserve the sequence of the four color fields.

A slight modification was necessary to the line and field scanning frequencies because one of the sidebands of the new color subcarrier fell right at the rest frequency of the FM sound carrier for system M, 4.5 MHz. Existing black-and-white receivers did not have adequate filtering to prevent an annoying buzz when the program sound was low and color saturation was high. By reducing the scanning frequencies by a mere 0.1%, the sidebands of luminance and chrominance remained interleaved, but shifted to eliminate the problem. Hence, the field frequency became 59.94 Hz, and the line frequency became 15.734 kHz.

Color-Difference Signals. Another suggestion came from Philco: Interference with the luminance signal is minimized by forming the two color signals as the difference between their respective primary and luminance (i.e., R − Y, B − Y).

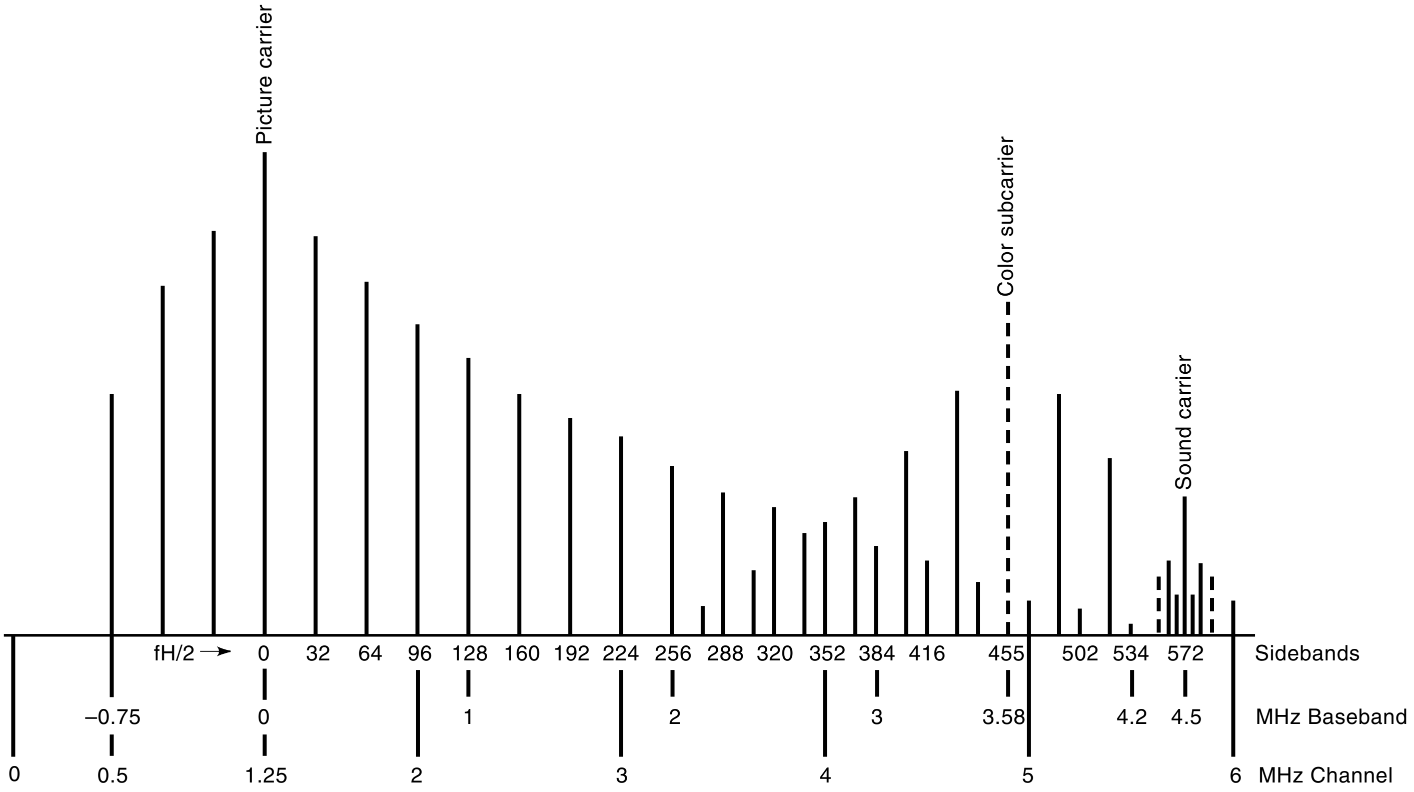


Figure 6. Frequency spectrum of composite NTSC-M color television signal showing relationships between the baseband and channel spectra and between sidebands of the picture carrier and color subcarrier.

This makes the color-difference signals smaller in amplitude since most scenes have predominantly pale colors.

The subcarrier itself is suppressed, so that only the sidebands are formed. When there is no color in the picture, the subcarrier vanishes. This necessitates a local oscillator at the receiver. A *color-burst* reference is inserted on the back porch of the horizontal sync pulse, which synchronizes the reference oscillator and provides an amplitude reference for color saturation automatic gain control.

Constant Luminance. With the constant-amplitude formulation ($Y = \frac{1}{3}R + \frac{1}{3}G + \frac{1}{3}B$), the luminance signal does not represent the exact scene brightness. Part of the brightness information is carried by the chrominance channels, so unwanted irregularities in them, such as noise and interference, produce brightness variations. Also, the gray-scale rendition of a color broadcast on a black-and-white receiver is not correct.

Hazeltine Electronics suggested weighting the contributions of the primaries to the luminance signal according to their actual addition to the displayed brightness. The color-difference signals will then represent only variations in hue and saturation, since they are "minus" the true brightness ($R - Y$, $B - Y$). A design based on this principle is called a *constant-luminance* system. For the display phosphors and white point originally specified, the luminance composition is $Y = 30\%\ R + 59\%\ G + 11\%\ B$.

Scaling Factors. The two low-bandwidth color-difference signals modulate a relatively high-frequency subcarrier superimposed onto the signal level representing luminance. However, the peak subcarrier excursions for some hues could reach far beyond the original black-and-white limits, where the complete picture signal is restricted between levels representing blanking and peak white picture information. Overmodulation at the transmitter may produce periodic suppression of the RF carrier and/or interference with the synchronizing signals. If the overall amplitude of the composite (luminance level plus superimposed subcarrier amplitude)

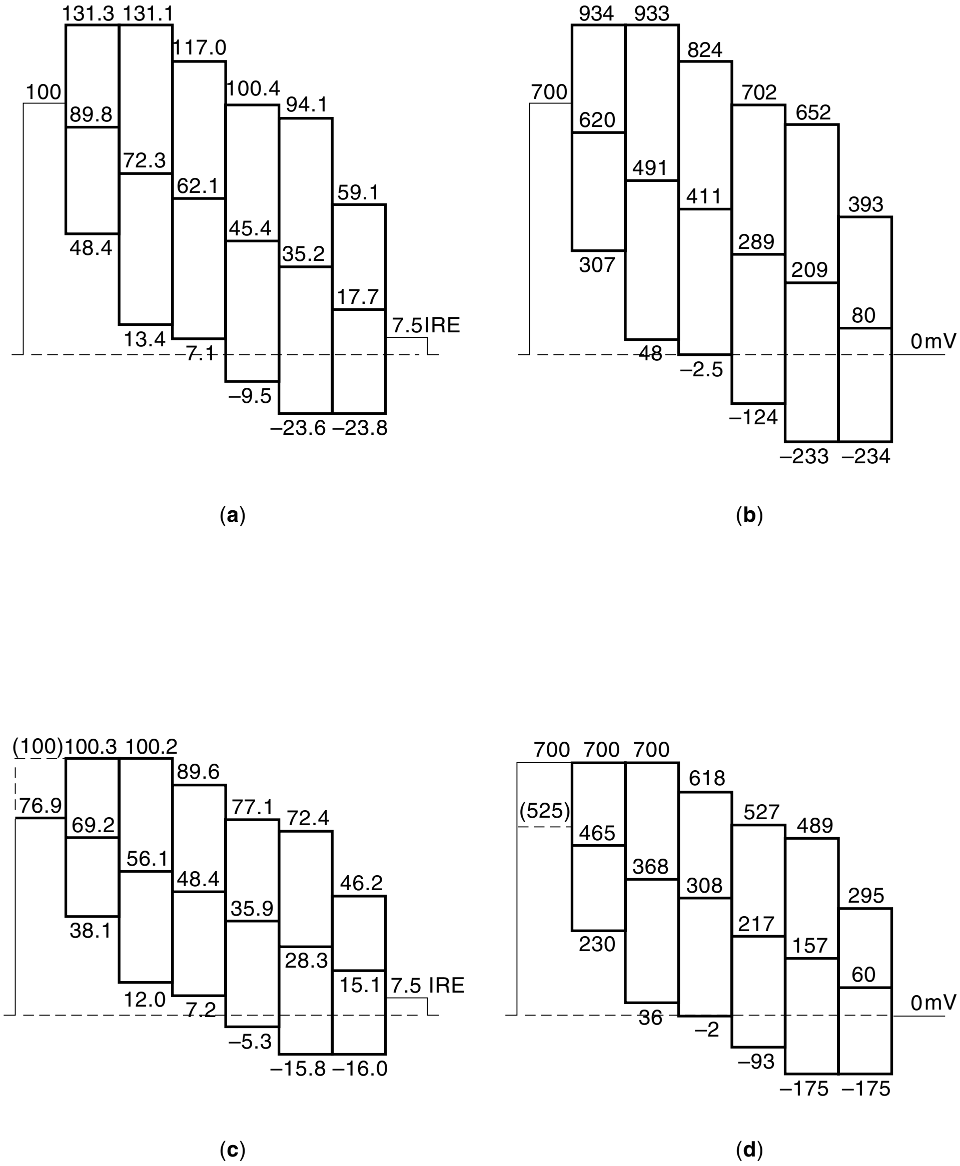


Figure 7. (a) 100% NTSC color bars (100/7.5/100/7.5). (b) 100% PAL color bars (100/0/100/0). (c) Standard 75% "EIA" color bars (75/7.5/75/7.5). (d) Standard 75% "EBU" color bars (100/0/75/0).

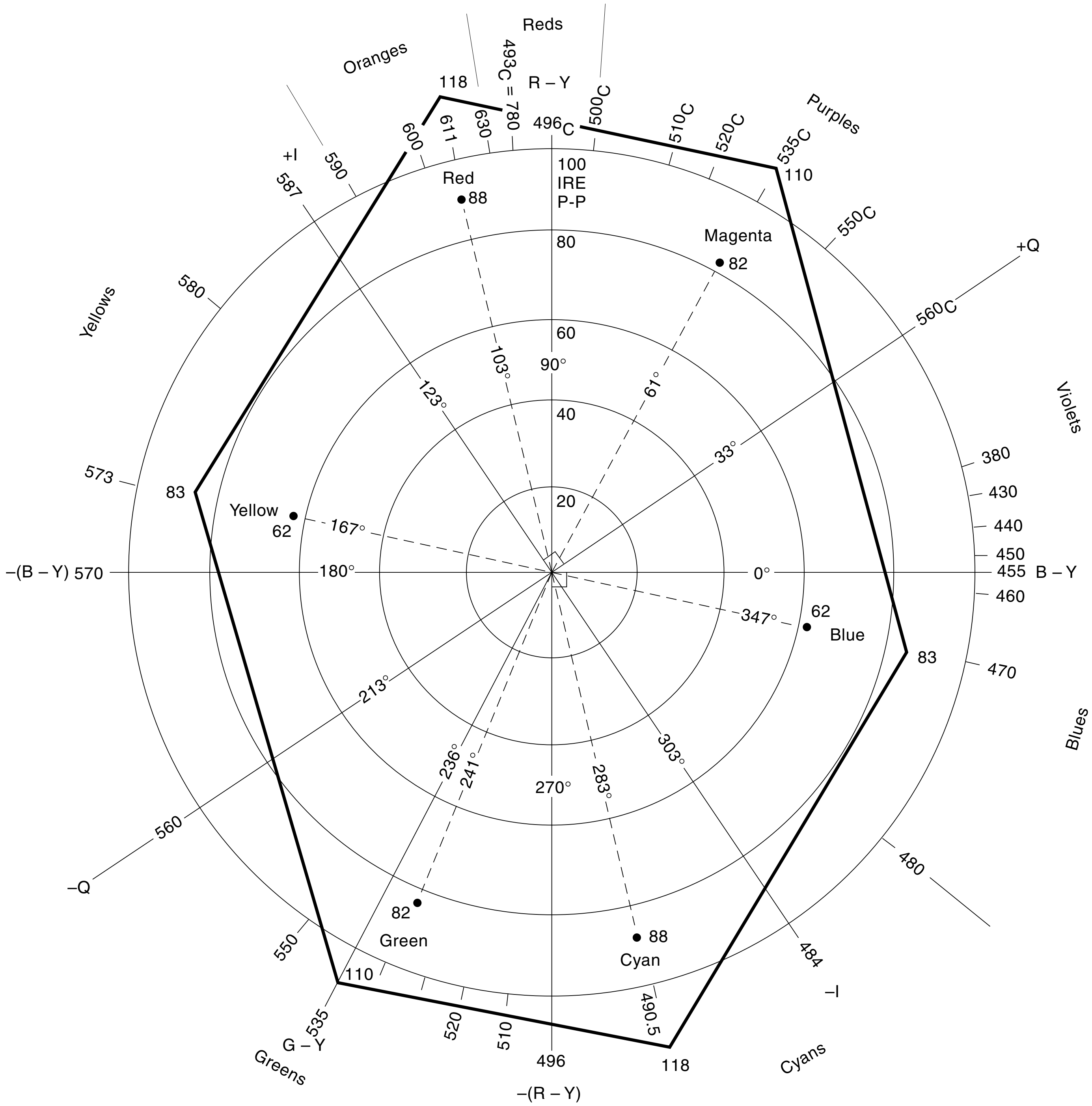


Figure 8. Vector relationship among chrominance components and corresponding dominant wavelengths. 75% Color bars with 7.5% setup. Linear NTSC system, NTSC luminophors, illuminant C. Hexagon defines maximum chrominance subcarrier amplitudes as defined by 100% color bars with 7.5% setup. *Caution:* The outer calibration circle on vectorscopes does *not* represent exactly 100 IRE P-P.

signal were simply lowered, the effective power of the transmitted signal would be significantly reduced.

A better solution was to reduce the overall amplitude of only the modulated subcarrier signal. However, such an arbitrary reduction would severely impair the signal-to-noise ratio of the chrominance information. The best solution proved to be selective reduction of each of the baseband R − Y and B − Y signal amplitudes to restrict the resulting modulated subcarrier excursions to $\pm\frac{4}{3}$ of the luminance signal levels. The R − Y signal is divided by 1.14, and B − Y is divided by 2.03. The resulting 33.3% overmodulation beyond both peak white and blanking levels was found to be an acceptable compromise, since the incidence of highly saturated colors is slight (Fig. 7).

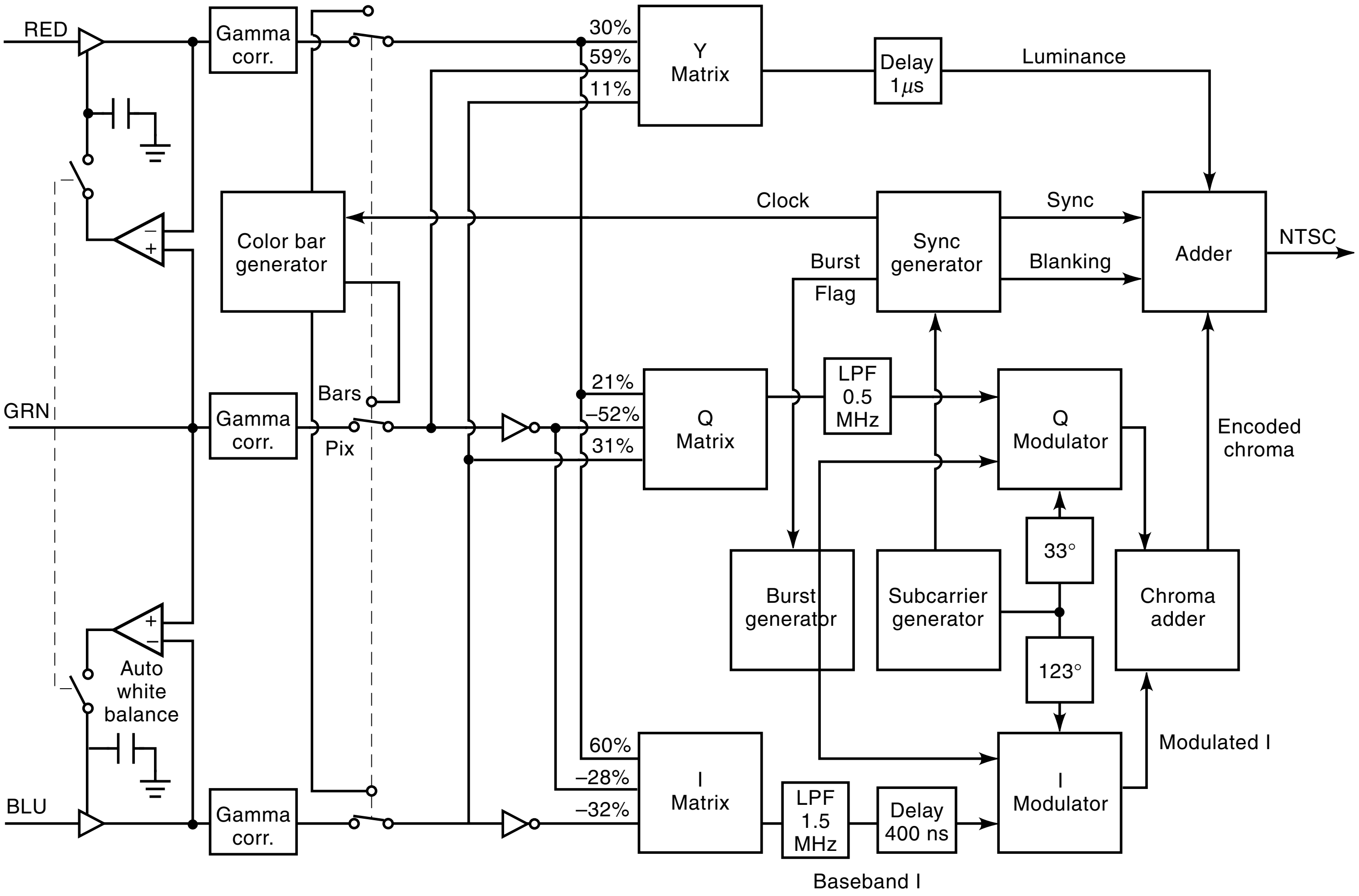


Figure 9. Block diagram of RGB to NTSC encoding (and related circuitry).

Proportioned Bandwidths. RCA proposed that the axes of modulation be shifted from R − Y, B − Y to conform to the greater and lesser acuity of human vision for certain colors. The new coordinates, called I and Q, are along the orange/cyan and purple/yellow-green axes. This was done so that the bandwidths of the two color signals could be proportioned to minimize crosstalk (Fig. 8).

Early receivers made use of the wider bandwidth of the I signal, however, it became evident that a very acceptable color picture could be reproduced with the I bandwidth restricted to the same as that of the Q channel. Virtually all NTSC receivers now employ "narrow-band" I channel decoding. A block diagram of NTSC color encoding is shown in Fig. 9. These recommendations were adopted by the American Federal Communications Commission in late 1953, and commercial color broadcasting was begun in early 1954.

Sequential and Memory (SECAM)

Economic devastation of World War II delayed the introduction of color television to Europe and other regions. Since differences between 525- and 625-line scanning standards made video tapes incompatible anyway, and satellite transmission was unheard of, there seemed little reason not to explore possible improvements to the NTSC process.

Sequential Frequency Modulation. The most tenuous characteristic of NTSC proved to be its sensitivity to distortion of the phase component of the modulated subcarrier. Since the phase component imparts color hue information, errors are quite noticeable, especially in skin tones. Also of concern was variations in the subcarrier amplitude, which affects the color saturation. Most long-distance transmission circuits in Europe did not have the phase and gain linearity to cope with the added color subcarrier requirements.

A solution to these drawbacks was devised by the Campagnie Française de Télévision in Paris. By employing a one-line delay in the receiver, quadrature modulation of the subcarrier could be discarded, and the color-difference signals (called D_R and D_B in SECAM) sent sequentially, on alternate lines. This reduces vertical resolution in color by half; however, it is sufficient to provide only coarse detail vertically, as is already the case horizontally.

In early development, AM was contemplated, however, the use of FM also eliminated the effects of subcarrier amplitude distortion. In addition, FM allowed the composite signal to be recorded on conventional black-and-white tape machines because precise time base correction, required by phase modulation, was not necessary.

Compatibility. With FM, the subcarrier is always present, superimposed on the luminance signal at constant amplitude

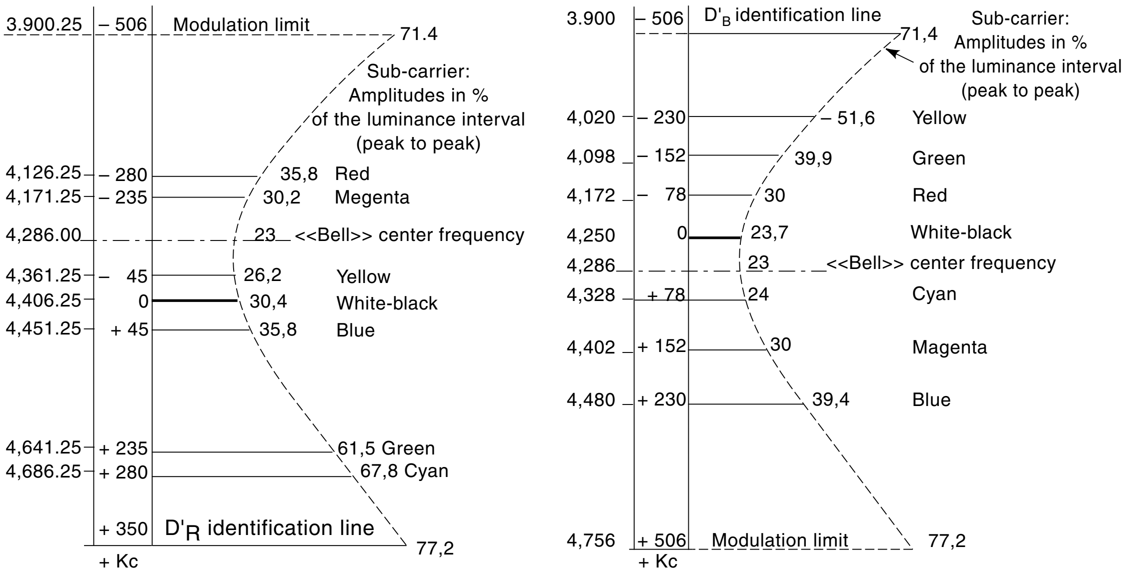


Figure 10. SECAM baseband (low-level) preemphasis.

(unlike NTSC, in which the subcarrier produces noticeable interference with the luminance only on highly saturated colors). To reduce its visibility, a number of techniques are employed.

Firstly, preemphasis is applied to the baseband color-difference signals to lessen their amplitudes at lower saturation, but preserve adequate signal-to-noise ratio (low-level preemphasis; see Fig. 10). Secondly, different subcarrier frequencies are employed, which are integral multiples of the scanning line frequency; f_{oB} is 4.25 MHz (272 H), and f_{oR} is 4.40625 MHz (282 H). The f_{oR} signal is inverted before modulation so that the maximum deviation is toward a lower frequency, reducing the bandwidth required for the dual subcarriers.

Thirdly, another level of preemphasis is applied to the modulated subcarrier around a point between the two rest frequencies, known as the “cloche” frequency of 4.286 MHz (high-level preemphasis, the so-called “anti-bell” shaping shown in Fig. 11). Finally, the phase of the modulated subcarrier is reversed on consecutive fields and, additionally, on every third scanning line, or, alternately, every three lines.

Line Identification. Synchronizing the receiver to the alternating lines of color-difference signals is provided in one of two ways. Earlier specifications called for nine lines of vertical blanking to contain a field identification sequence formed by truncated sawteeth of the color-difference signals from the white point to the limiting frequency (so-called “bottles”; see Fig. 12). This method is referred to as “SECAM-V.”

As use of the vertical interval increased for ancillary signals, receiver demodulators were fashioned to sample the unblanked subcarrier immediately following the horizontal sync pulse, providing an indication of line sequence from the rest frequency. Where this method is employed, it is called “SECAM-H.” An advantage of this method is near-instantaneous recovery from momentary color field sequence errors, whereas SECAM-V receivers must wait until the next vertical interval.

Issues in Program Production. High-level preemphasis causes the chrominance subcarrier envelope to increase in amplitude at horizontal transitions, as can be seen on a waveform monitor (Fig. 13). Unlike NTSC, the subcarrier amplitude bears no relation to saturation, so, except for testing purposes, a luminance low-pass filter is employed on the waveform monitor. A vectorscope presentation of the satura-

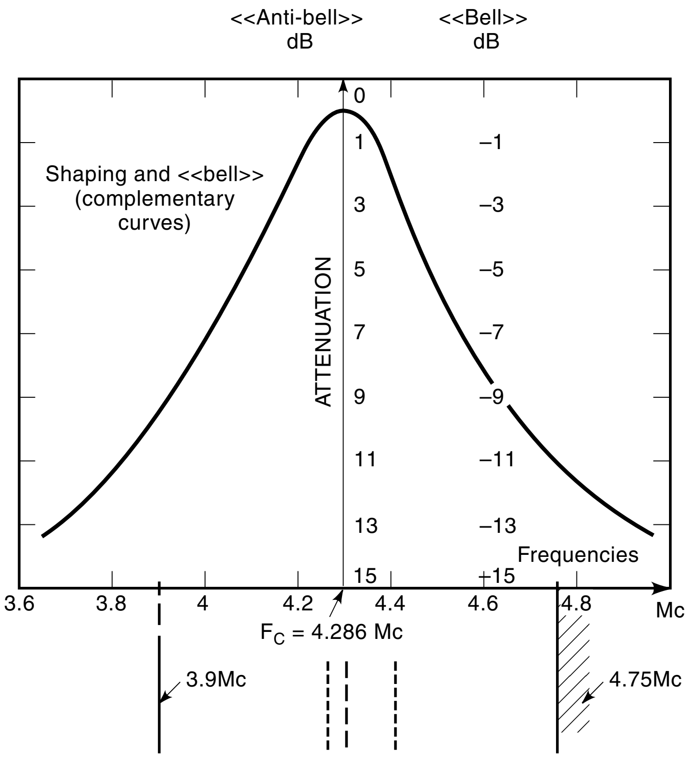


Figure 11. SECAM RF (high-level) preemphasis.

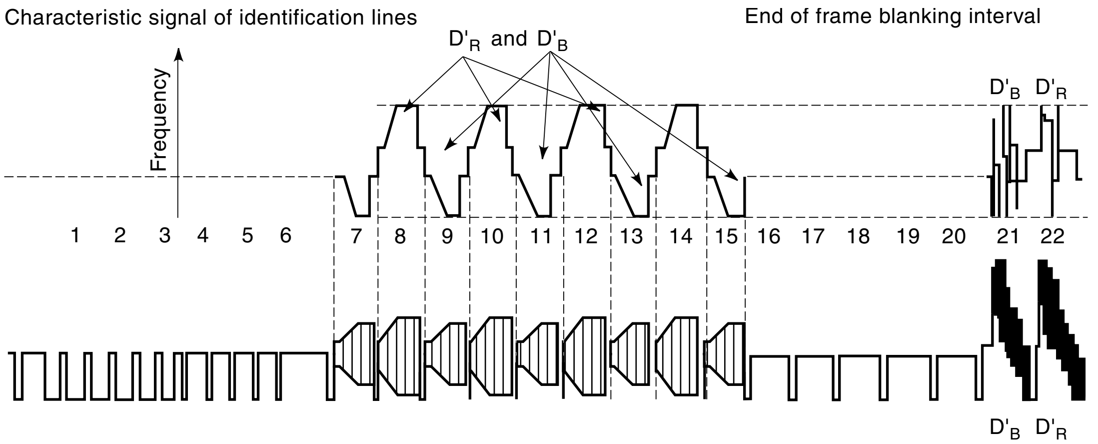


Figure 12. SECAM field identification "bottles."

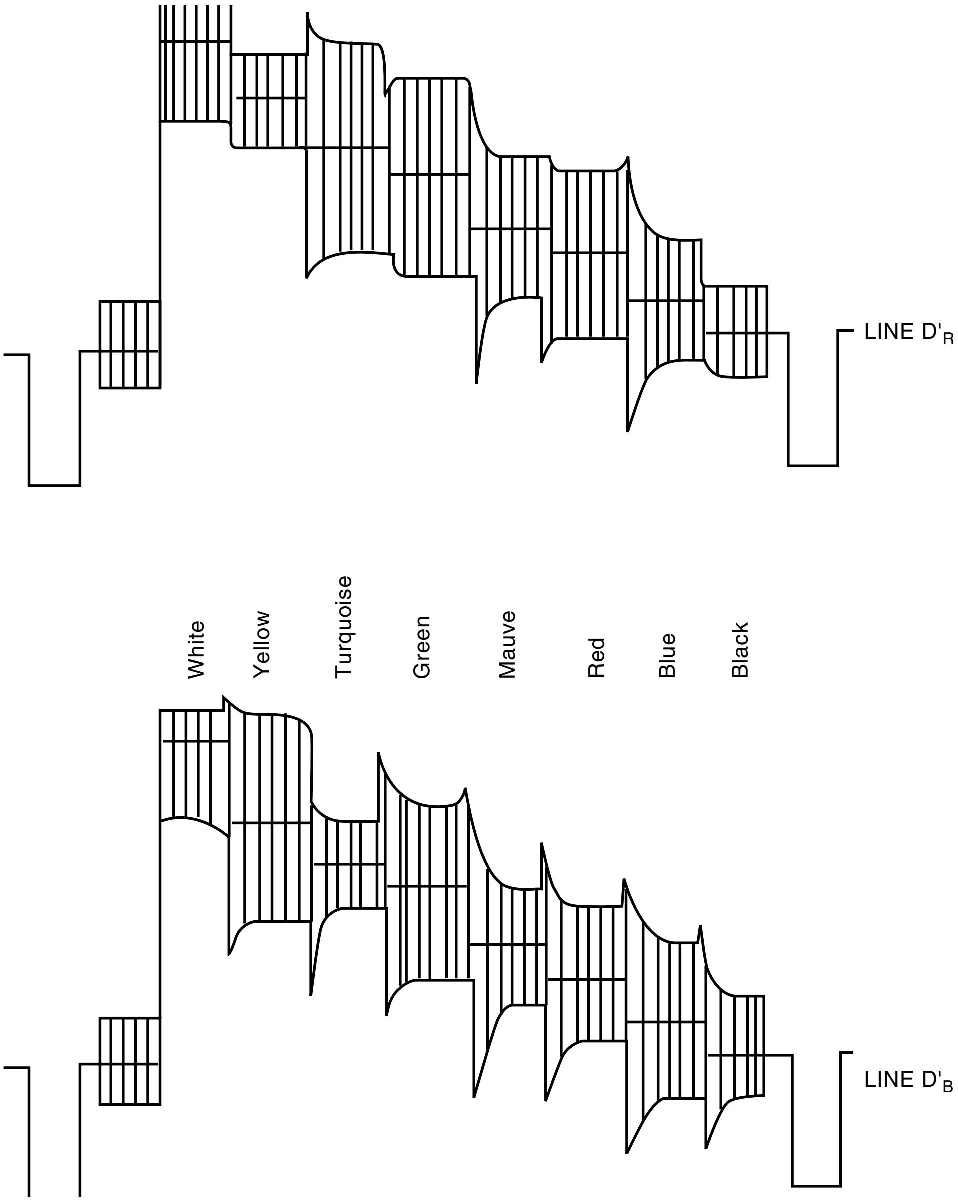


Figure 13. SECAM color bar waveforms.

tion and hue is implemented by decoding the FM subcarrier into baseband color-difference signals and applying them to an *X*–*Y* display.

Unfortunately, the choice of FM for the color subcarrier means that conventional studio production switchers cannot be employed for effects such as mixing or fading from one scene to another because reducing the amplitude of the subcarrier does not reduce the saturation. This necessitates using a component switcher and then using encoding afterwards. In cases where the signal has already been encoded to SECAM (such as from a prerecorded video tape), it must be decoded prior to the component switcher and then reencoded.

Like NTSC, program editing must be done in two-frame increments. Although the subcarrier phase is reversed on a field-and-line basis, establishing a “12-field sequence,” it is the instantaneous frequency—not phase—which defines the hue. However, the line-by-line sequence of the color-difference signals must be maintained. The odd number of scanning lines means that each successive frame begins with the opposite color-difference signal. As described above, mixes or fades are never done with composite signals.

Since the instantaneous frequency of the subcarrier is not related to the line scanning frequency, it is impossible to employ modern comb-filtering techniques to separate the chrominance and luminance in decoding. Increasingly, special effects devices rely on decoding the composite TV signal to components for manipulation, then reencoding. Every operation of this sort impairs luminance resolution because a notch filter must be used around the subcarrier frequency. These concerns have led many countries which formerly adopted SECAM to switch to PAL for program production, transcoding to SECAM only for RF broadcasting.

Phase Alternate Line (PAL)

To retain the ease in program production of NTSC, yet correct for phase errors, the German Telefunken Company developed a system more comparable to NTSC which retains quadrature modulation. Because of the wider channel bandwidth associated with 625-line systems, the color subcarrier could be positioned so that the sidebands from both color-difference signals have the same bandwidth. This means that R − Y and B − Y signals could be used directly, rather than I and Q as in NTSC. Identical scaling factors are used, and the signals are known as V and U, respectively.

Color Phase Alternation. In the PAL System, the phase of the modulated V component of the chrominance signal is reversed on alternate lines to cancel chrominance phase distortion acquired in equipment or transmission. Any phase shift encountered will have the opposite effect on the displayed hue on adjacent lines in the picture. If the phase error is limited to just a few degrees, the eye integrates the error, since, in the vertical direction, more chrominance detail is provided than can be perceived at normal viewing distances. Receivers based on this principle are said to have “simple PAL” decoders.

If the phase error is more than a few degrees, the difference in hue produces a venetian-blind effect, called *Hanover bars.* Adding a one-line delay permits integrating chrominance information from adjacent scanning lines electrically, with a slight reduction in the saturation for large errors. Color resolution is reduced by half in the vertical direction, but more closely matches horizontal resolution due to bandlimiting in the encoder. This technique of decoding is called “deluxe PAL.” A reference is provided to indicate which lines have $+V$ or $-V$ phase by also shifting the phase of the color burst signal by ±45° on alternate lines.

Compatibility. The line-by-line phase reversal results in identical phase on alternate lines for hues on or near the *V* axis. To sustain a low-visibility interference pattern in PAL, the subcarrier frequency is made an odd multiple of one-quarter of the line frequency (creating eight distinct color fields). This effectively offsets the excursions of the *V* component by 90° line-to-line and offsets those of the *U* component by 270°. Since this 180° difference would cause the excursions of one component to line up vertically with those of the other in the next frame, an additional 25 Hz offset ($f_V/2$) is added to the PAL subcarrier frequency to further reduce its visibility.

In early subcarrier oscillator designs, the reference was derived from the mean phase of the alternating burst signal. Interlaced scanning causes a half-line offset between fields with respect to the vertical position so that the number of bursts actually blanked during the $7\frac{1}{2}$H vertical interval would be different for the odd versus even fields. Since the phase of burst alternates line-to-line, the mean phase would then appear to vary in this region, causing disturbances at the top of the picture.

This is remedied by a technique known as “Bruch blanking.” The burst blanking is increased to a total of nine lines, and repositioned in a four-field progression to include the $7\frac{1}{2}$H interval, such that the first and last burst of every field has a phase corresponding to $(-U + V)$, or +135°. The burst signal is said to “meander” so that color fields 3 and 7 have the earliest bursts.

Issues in Program Production. In PAL, since the subcarrier frequency is an odd multiple of one-quarter the line frequency, each line ends on a quarter-cycle. This, coupled with the whole number plus one-half lines per field, causes the phase of subcarrier to be offset each field by 45°. Thus, in PAL, the subcarrier phase repeats only every eight fields, creating an “eight-field sequence.” This complicates program editing, because edit points occur only every four frames, which is slightly less than 1/10 s in time.

Comb filtering to separate chrominance and luminance in decoding is somewhat more complicated in PAL; however, it has become essential for special picture effects. On a waveform monitor, the composite PAL signal looks very much like NTSC, except that the 25 Hz offset causes a slight phase shift from line to line, so that when viewing the entire field, the sine wave pattern is blurred. Because of the reversal in phase of the *V* component on alternate lines, the vectorscope presentation has a mirror image about the *V* axis (Fig. 14).

Variations of PAL. The differences between most 625-line transmission standards involve only RF parameters (such as sound-to-picture carrier spacing). For 625-line PAL program production, a common set of technical specifications may be used. These standards are routinely referred to in the production environment as “PAL-B,” although the baseband signals may be used with any 625-line transmission standard.

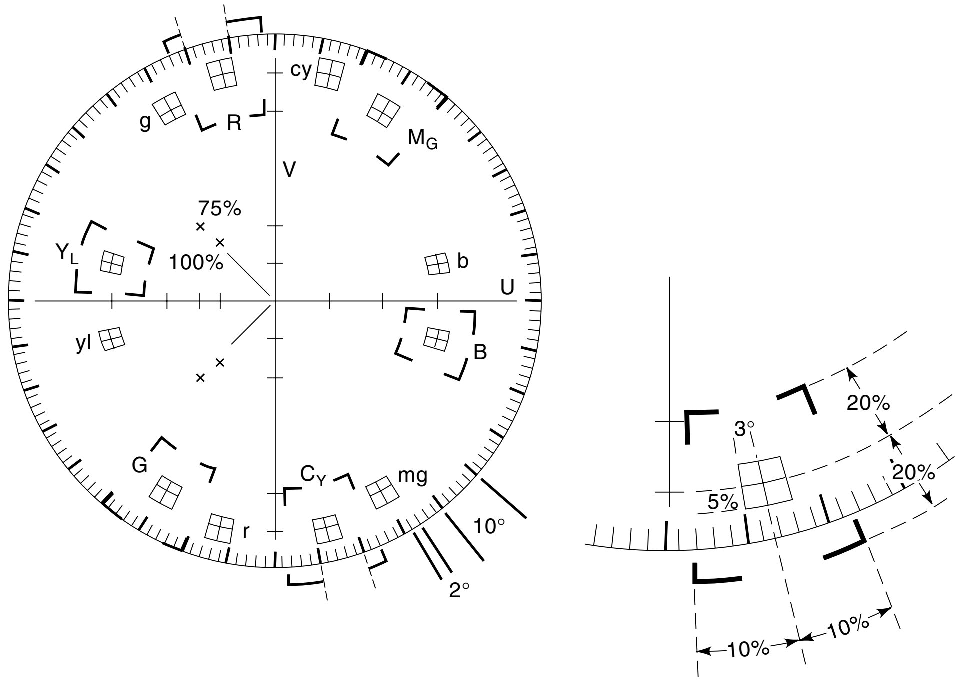


Figure 14. Typical PAL vectorscope graticule.

Several countries in South America have adopted the PAL system. The 6 MHz channel allocations in that region meant that the color subcarrier frequency had to be suitably located, about 1 MHz lower in frequency than for 7 MHz or 8 MHz channels. The exact frequencies are close to, but not the same as, those for NTSC. The 625-line system is known as PAL-N. Studio production for this standard is done in conventional "PAL-B," then converted to PAL-N at the transmitter.

The 525-line PAL is known as PAL-M, and it requires studio equipment unique to this standard, although the trend is toward using conventional NTSC-M equipment and also transcoding to PAL-M at the transmitter. PAL-M does not employ a 25 Hz offset of the subcarrier frequency, as is done in all other PAL systems.

Similarities of Color Encoding Systems

The similarities of the three basic color television encoding systems are notable (see Table 3). They all rely on the concept of a separate luminance signal which provides compatibility with black-and-white television receivers. The "mixed-highs" principle combines high-frequency information from the three color primaries into luminance, where the eye is sensitive to fine detail; only the relatively low-frequency information is used for the chrominance channels. All three systems use the concept of a subcarrier, located in the upper-frequency spectrum of luminance, to convey the chrominance information (Fig. 15).

All systems use color-difference signals, rather than the color primaries directly, to minimize crosstalk with the luminance signal, and all derive the third color signal by subtracting the other two from luminance. The constant luminance principle is applied in all systems, based on the original NTSC picture tube phosphors, so the matrix formulations for luminance and color-difference signals are identical (some recent NTSC encoders use equal-bandwidth R − Y and B − Y signals, instead of proportioned-bandwidth I and Q signals).

All of the systems use scaling factors to limit excessive subcarrier amplitude (NTSC/PAL) or deviation (SECAM) excursions. Finally, all three systems use an unmodulated subcarrier sample on the back porch of the horizontal sync pulse for reference information in the decoding process.

Because of these similarities, conversion of signals between standards for international program distribution is possible. Early *standards converters* were optical in nature, essentially using a camera of the target standard focused on a picture tube operating at the source standard. Later, especially for color, electronic conversion became practical.

The most serious issue in standards conversion involves motion artifacts, owing to the different field rates between 525 and 625-line systems. Simply dropping or repeating fields and lines creates disturbing discontinuities, so interpolation must be done. In modern units, the composite signals are decoded into components, using up to three-dimensional adaptive comb filtering, converted using motion prediction, then re-encoded to the new standard. Table 4 lists the transmission and color standards used in various territories throughout the world.

Component Analog Video (CAV)

The advent of small-format video tape machines which recorded luminance and chrominance on separate tracks led to interest in component interconnection. Increasingly, new equipment decoded and reencoded the composite signal to perform manipulations which would be impossible or cause significant distortions if done in the composite environment. It was reasoned that if component signals (Y, R − Y, B − Y) could be taken from the camera and if encoding to NTSC, PAL, or SECAM could be done just prior to transmission, then technical quality would be greatly improved.

Table 3. Principal Characteristics of Color Television Encoding Systems

System	NTSC	PAL	SECAM
Display primaries	FCC	EBU	EBU
White reference	CIE Ill C	CIE Ill D_{65}	CIE Ill C
Display gamma	2.2	2.8	2.8
Luminance	$E'_Y = +0.30E'_R + 0.59E'_G + 0.11E'_B$	$E'_Y = +0.299E'_R + 0.587E'_G + 0.114E'_B$	
Chrominance signals	$Q = +0.41\ (B - Y) + 0.48\ (R - Y)$ $I = -0.27\ (B - Y) + 0.74\ (R - Y)$	$U = 0.493\ (B - Y)$ $V = 0.877\ (R - Y)$	$D_B = +1.505\ (B - Y)$ $D_R = -1.902\ (R - Y)$
Chrominance baseband video preemphasis (kHz)	—	—	$D^*_B = A \times D_R$ $D^*_R = A \times D_R$ $A = \left\|\dfrac{1 + j \times \dfrac{f_B/f_R}{85}}{1 + j \times \dfrac{f_B/f_R}{255}}\right\|$
Modulation method	Amplitude modulation of two suppressed subcarriers in quadrature		Frequency modulation of two sequential subcarriers
Axes of modulation	$Q = 33°,\ I = 123°$	$U = 0°,\ V = \pm 90°$	—
Chroma BW/Deviation (kHz)	$Q = 620,\ I = 1300$	$U + V = 1300$	$\Delta f_{oB} = \pm 230\ +276/-120$, $\Delta f_{oR} = \pm 280\ +70/-226$
Vestigial sideband (kHz)	+620	+570 (PAL-B,G,H), +1070 (PAL-I), +620 (PAL-M,N)	—
Composite color video signal (CCVS)	$E_M = E'_Y + E'_Q\ (\sin \omega t + 33°)$ $+ E'_I\ (\cos \omega t + 33°)$	$E_M = E'_Y + E'_U \sin \omega t$ $\pm E'_V \cos \omega t$	$E_M = E'_Y + G_{SC} \times \cos 2\pi(f_{oB} + D^*_B\ \Delta f_{oB})\ t$ $+ G_{SC} \times \cos 2\pi(f_{oR} + D^*_B\ \Delta f_{oR})\ t$
Modulated subcarrier amplitude/preemphasis	$G_{SC} = \sqrt{E'^2_Q + E'^2_I}$	$G_{SC} = \sqrt{E'^2_U + E'^2_V}$	$G_{SC} = D^*_B/D^*_R \times 0.115E'_Y(P{-}P) \times \left\|\dfrac{1 + j(16)F}{1 + j(1.26)F}\right\|$ $F = \dfrac{f_B/f_R}{f_0} - \dfrac{f_0}{f_B/f_R}\quad (f_0 = 4.286 \pm 0.02\ \text{MHz})$
SC/H frequency relationship	$f_{SC} = (455/2)f_H$	$f_{SC} = (1135/4)f_H + f_V/2$ (PAL-B, G, H, I) $= (909/4)f_H$ (PAL-M) $= (917/4)f_H + f_V/2$ (PAL-N)	$f_{oB} = 272f_{H'}\ f_{oR} = 282f_H$
Subcarrier frequency (MHz)	3.579545 ± 10 Hz	4.43361875 ± 5 Hz (PAL-B, G, H); ±1 Hz (PAL-I) 3.57561149 ± 10 Hz (PAL-M) 3.58205625 ± 5 Hz (PAL-N)	$f_{oB} = 4.250000 \pm 2$kHz, $f_{oR} = 4.406250 \pm 2$kHz
Phase/Deviation of SC reference	180°	$+V = +135°,\ -V = -135°$	$D_B = -350$ kHz, $D_R = +350$ kHz
Start of SC reference (μs)	5.3 ± 0.1	5.6 ± 0.1 (PAL-B, G, H, I, N); 5.2 ± 0.5 (PAL-M)	5.7 ± 0.3
SC reference width (cycles)	9 ± 1	10 ± 1 (PAL-B, G, H, I); 9 ± 1 (PAL-M, N)	—
SC reference amplitude (mV)	286 (40 IRE ± 4)	300 ± 30	$D_B = 167$, $D_R = 215$

However, component signal distribution required some equipment, such as switchers and distribution amplifiers, to have three times the circuitry, and interconnection required three times the cable and connections as composite systems. This brought about consideration of *multiplexed analog component* (MAC) standards, whereby the luminance and chrominance signals are time-multiplexed into a single, higher-bandwidth signal. No single standard for component signal levels emerged (Table 5), and the idea was not widely popular. Interest soon shifted to the possibility of digital signal distribution.

Digital Video

Devices such as time-base correctors, frame synchronizers, and standards converters process the TV signal in the digital realm but with analog interfaces. The advent of digital video tape recording set standards for signal sampling and quantization to the extent that digital interconnection became practical.

Component Digital. The European Broadcasting Union (EBU) and Society of Motion Picture and Television Engineers (SMPTE) coordinated research and conducted demonstrations in search of a component digital video standard which would lend itself to the exchange of programs on a worldwide basis. A *common data rate* of 13.5 Mbps based on line-locked sampling of both 525- and 625-line standards was chosen. This allows analog video frequencies of better than 5.5 MHz to be recovered, and is an exact harmonic of the scanning line rate for both standards, enabling great commonality in equipment.

A *common image format* of static orthogonal shape is also employed, whereby the sampling instants on every line coincide with those on previous lines and fields and also overlay the samples from previous frames. There are 858 total luminance samples per line for the 525-line system, 864 samples for the 625-line system, but 720 samples during the picture portion for both systems. This image structure facilitates filter design, special effects, compression, and conversion between standards.

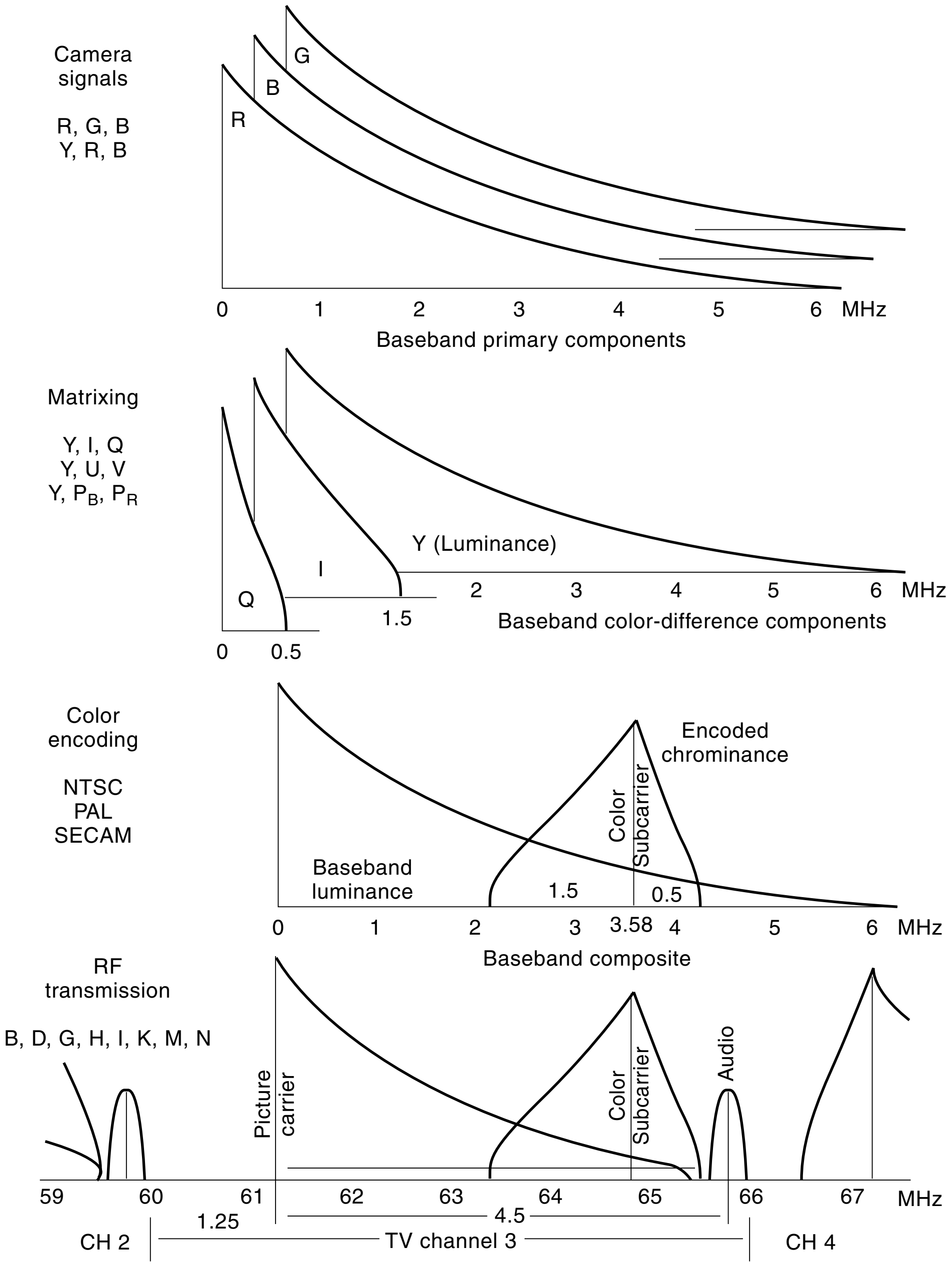


Figure 15. Four-stage color television frequency spectrum, showing the compression of three wide-band color-separation signals from the camera through bandwidth limiting and frequency multiplexing into the same channel bandwidth used for black-and-white television.

For studio applications, the color-difference signals are sampled at half the rate of luminance, or 6.75 MHz, co-sited with every odd luminance sample, yielding a total data rate of 27 Mbps. This provides additional resolution for the chrominance signals, enabling good special effects keying from color detail. The sampling ratio for luminance and the two chrominance channels is designated "4 : 2 : 2." Other related ratios are possible (Table 6).

Quantization is uniform (not logarithmic) for both luminance and color-difference channels. Eight-bit quantization, providing 256 discrete levels, was found to provide adequate signal-to-noise ratio for video tape applications. However, the 25-pin parallel interface selected can accommodate two extra bits, since 10-bit quantization was foreseen as desirable in the future. Only the active picture information is sampled and quantized, allowing better resolution of the signal amplitude. Sync and blanking are coded by special signals (Figs. 16 and 17).

These specifications were standardized in ITU-R BT.601—hence the abbreviated reference, "601 Video." The first component digital tape machine standard was designated "D1" by SMPTE. This term has come to be used in place of more correct designations. For wide-screen applications, a 360 Mbps standard scales up the number of sampling points for 16 : 9 aspect ratio.

Interconnecting digital video equipment is vastly simplified by using a serial interface. Originally, an 8/9 block code was devised to facilitate clock recovery by preventing long strings of ones or zeros in the code. This would have resulted in a serial data rate of 243 Mbps. To permit 10-bit data to be

Table 4. National Television Transmission Standards

Territory	VHF	UHF	Color
Afars and Isaas = Djibouti			
Afghanistan	D		PAL
Albania	B	G	PAL
Algeria	B		PAL
Andorra	B		PAL
Angola	I		PAL
Antigua and Barbuda	M		NTSC
Argentina	N		PAL
Armenia	D	K	SECAM
Ascension Islands	I		
Australia	B	B	PAL
Austria	B	G	PAL
Azerbaijan	D	K	SECAM
Azores	B		PAL
Bahamas	M		NTSC
Bahrain	B	G	PAL
Bangladesh	B		PAL
Barbados	M		NTSC
Belarus	D	K	SECAM
Belgium	B	H	PAL
Benin	K′		SECAM
Bermuda	M		NTSC
Bolivia	M	M	NTSC
Bosnia and Herzegovina	B	G	PAL
Botswana	I		PAL
Brazil	M		PAL
Brunei Darussalam	B		PAL
Bulgaria	D	K	P & S
Burkina Faso	K′		SECAM
Burma = Myanmar			
Burundi		K′	SECAM
Cambodia	B		PAL
Cameroon	B		PAL
Canada	M	M	NTSC
Canary Islands	B	G	PAL
Cape Verde Islands	I		PAL
Cayman Islands	M		NTSC
Central African Republic	K′		SECAM
Ceylon = Sri Lanka			
Chad	K′		SECAM
Channel Islands		I	PAL
Chile	M		NTSC
China	D	D	PAL
Colombia	M		NTSC
Commonwealth of Independent States: see state			
Comores	K′		
Congo	K′		SECAM
Costa Rica	M		NTSC
Côte d’Ivoire	K′		SECAM
Croatia	B	G	PAL
Cuba	M		NTSC
Curaco	M	M	NTSC
Cyprus	B	G	P & S
Czech Republic	D	K	S P
Dahomey = Benin			
Denmark	B	G	PAL
Diego Garcia	M		NTSC
Djibouti	K′		SECAM
Dominican Republic	M		NTSC
Ecuador	M		NTSC
Equtorial Guinea = Fernando Po			
Egypt	B	G	P & S
El Salvador	M		NTSC
Eritrea	B		PAL
Estonia	D	K	SECAM
Ethiopia	B		PAL
Faeroe Islands	B	G	PAL
Falkland Islands	I		PAL
Fernando Po	B		PAL
Fiji	M		NTSC
Finland	B	G	PAL
France	L′	L	SECAM
French Guyana	K′		SECAM
French Polynesia	K′		SECAM
Gabon	K′		SECAM
Gambia	B		PAL
Georgia	D	K	SECAM
Germany	B	G	PAL
Ghana	B		PAL
Gibraltar	B	G	PAL
Greece	B	G	SECAM
Greenland	B		PAL
Grenada	M		NTSC
Guadeloupe	K′		SECAM
Guam	M	M	NTSC
Guatemala	M		NTSC
Guinea	K′		PAL
Guinea-Bissau	I		
Guyana, Republic of	M		NTSC
Haiti	M		NTSC
Honduras	M		NTSC
Hong Kong		I	PAL
Hungary	D	K	P & S
Iceland	B	G	PAL
India	B		PAL
Indonesia	B		PAL
Iran	B		SECAM
Iraq	B		SECAM
Ireland	I	I	PAL
Israel	B	G	PAL
Italy	B	G	PAL
Ivory Coast = Côte d’Ivoire			
Jamaica	M		NTSC
Japan	M	M	NTSC
Johnston Islands	M		NTSC
Jordan	B	G	PAL
Kampuchea = Cambodia			
Kazakhstan	D	K	SECAM
Kenya	B		PAL
Korea, Democracy of (N)	D		PAL
Korea, Republic of (S)	M	M	NTSC
Kuwait	B	G	PAL
Kyrgyzstan	D	K	SECAM
Laos	B		PAL
Latvia	D	K	SECAM
Lebanon	B	G	SECAM
Leeward Islands = Antigua			
Lesotho	I		PAL
Liberia	B		PAL
Libya	B		SECAM
Lichtenstein	B	G	PAL
Lithuania	D	K	SECAM
Luxembourg	B	G/L	P P/S
Macao		I	PAL
Macedonia	B	G	PAL
Madagascar	K′		SECAM
Madeira	B		PAL
Malawi	B		PAL
Malaysia	B		PAL
Maldives	B		PAL
Mali	K′		SECAM
Malta	B		PAL
Martinique	K′		SECAM
Mauritania	B		SECAM
Mauritius	B		SECAM
Mayotte	K′		SECAM
Mexico	M	M	NTSC
Micronesia	M		NTSC
Moldovia	D	K	SECAM
Monaco	L	G/L	S P/S
Mongolia	D		SECAM
Montserrat	M		NTSC
Morocco	B		SECAM
Mozambique		B	PAL
Myanmar	M		NTSC
Namibia	I		PAL
Nepal	B		PAL
Netherlands	B	G	PAL
Netherlands Antilles	M		NTSC
New Caledonia	K′		SECAM
New Zealand	B	G	PAL
Nicaragua	M		NTSC
Niger	K′		SECAM
Nigeria	B		PAL
Norway	B	G	PAL
Oman	B	G	PAL
Pakistan	B		PAL
Palau	M		NTSC
Panama	M		NTSC
Papua New Guinea	B	G	PAL
Paraguay	N		PAL
Peru	M	M	NTSC
Philippines	M		NTSC
Poland	D	K	P & S
Portugal	B	G	PAL
Puerto Rico	M	M	NTSC
Qatar	B	G	PAL
Reunion	K′		SECAM
Romania	D	G/K	PAL
Russia	D	K	SECAM
Rwanda	K′		
St. Helena	I		
St. Pierre et Miquelon	K′	K′	SECAM
St. Kitts and Nevis	M		NTSC
Samoa (American)	M		NTSC
Samoa (Western)	B		PAL
São Tomé e Princípe	B		PAL
San Andres Islands	M		NTSC
San Marino	B	G	PAL
Saudi Arabia	B	G	S/P S
Senegal	K′		SECAM
Serbia	B	G	PAL
Seychelles	B		PAL
Sierra Leone	B		PAL
Singapore	B		PAL
Slovakia	B	G/K	PAL
Slovenia	B	G	PAL
Society Islands = French Polynesia			
Somalia	B		PAL
South Africa	I	I	PAL
S. West Africa = Namibia			
Spain	B	G	PAL
Sri Lanka	B		PAL
Sudan	B		PAL
Suriname	M		NTSC
Swaziland	B	G	PAL
Sweden	B	G	PAL
Switzerland	B	G	PAL
Syria	B	G	P & S
Tahiti = French Polynesia			
Taiwan	M	M	NTSC
Tajikistan	D	K	SECAM
Tanzania	B	I	PAL
Thailand	B	M	P N
Togo	K′		SECAM
Trinidad and Tobago	M	M	NTSC
Tunisia	B	G	P S
Turks and Caicos	M		NTSC
Turkey	B	G	PAL
Turkmenistan	D	K	SECAM
Uganda	B		PAL
Ukraine	D	K	SECAM
USSR: see independent state			
United Arab Emirates	B	G	PAL
United Kingdom		I	PAL
United States	M	M	NTSC
Upper Volta = Burkina Faso			
Uruguay	N		PAL
Uzbekistan	D	K	SECAM
Venezuela	M		NTSC
Vietnam	D/M		S/N
Virgin Islands	M		NTSC
Yemen	B		PAL
Yugoslavia: see new state			
Zaire	K′		SECAM
Zambia	B		PAL
Zanzibar = Tanzania			
Zimbabwe	B		PAL

Table 5. Component Analog Video Format Summary

	Color Bar Amplitudes (mV)			Peak Excursions (mV)		
	Channel 1	Channel 2	Channel 3			
Format	100% 75%	100% 75%	100% 75%	Synchronization Channels/Signals		Setup
R/G/B/S[a]	+1 V/+750	+1 V/+750	+1 V/+750	S = −4 V		No
G/B/R	+700/+525	+700/+525	+700/+525	G, B, R = −300		No
Y/I/Q (NTSC)	+714/+549	±393/±295	±345/±259	Y = −286		Yes
Y/Q/I (M_I)	+934/+714	±476/±357	±476/±357	Y = −286	I = −600	Yes
Y/R − Y/B − Y*	+700/+525	±491/±368	±620/±465	Y = −300		No
Y/U/V (PAL)	+700/+525	±306/±229	±430/±323	Y = −300		No
Betacam 525	+714/+549	±467/±350	±467/±350	Y = −286		Yes
2 CH Y/CTDM	+714/+549	±467/±350		Y = ±286	C = −420	
Betacam 625	+700/+525	±467/±350	±467/±350	Y = −300		No
2 CH Y/CTDM	+700/+525	±467/±350		Y = ±300	C = −420	
M_{II} 525	+700/+538	±324/±243	±324/±243	Y = −300		Yes
2 CH Y/CTCM	+714/+549	±350/±263		Y = −286	C = −650	
M_{II} 625	+700/+525	±350/±263	±350/±263	Y = −300		No
2 CH Y/CTCM	+700/+525	±350/±263		Y = −300	C = −650	
SMPTE/EBU ($Y/P_B/P_R$)	+700/+525	±350/±263	±350/±263	Y = −300		No

[a] Other levels possible with this generic designation.

serialized, scrambling is employed, with complementary descrambling at the receiver. NRZI coding is used, so the fundamental frequency is half the bit-rate of 270 MHz.

Composite Digital. Time-base correctors for composite 1 in. video tape recorders had been developed with several lines storage capability. Some early devices sampled at three times the color subcarrier frequency ($3f_{sc}$); however, better filter response could be obtained with $4f_{sc}$ sampling. The sampling instants correspond with peak excursions of the I and Q subcarrier components in NTSC. The total number of samples per scanning line is 910 for NTSC and is 1135 for PAL. To

Table 6. Sampling Structures for Component Systems

	Sample/Pixel				
	1	2	3	4	5
Line	YC_bC_r	YC_bC_r	YC_bC_r	YC_bC_r	YC_bC_r
	$\mathbf{YC_bC_r}$	$\mathbf{YC_bC_r}$	$\mathbf{YC_bC_r}$	$\mathbf{YC_bC_r}$	$\mathbf{YC_bC_r}$
	YC_bC_r	YC_bC_r	YC_bC_r	YC_bC_r	YC_bC_r
	$\mathbf{YC_bC_r}$	$\mathbf{YC_bC_r}$	$\mathbf{YC_bC_r}$	$\mathbf{YC_bC_r}$	$\mathbf{YC_bC_r}$
			4:4:4		

	Sample/Pixel				
	1	2	3	4	5
Line	YC_bC_r	Y	YC_bC_r	Y	YC_bC_r
	$\mathbf{YC_bC_r}$	**Y**	$\mathbf{YC_bC_r}$	**Y**	$\mathbf{YC_bC_r}$
	YC_bC_r	Y	YC_bC_r	Y	YC_bC_r
	$\mathbf{YC_bC_r}$	**Y**	$\mathbf{YC_bC_r}$	**Y**	$\mathbf{YC_bC_r}$
			4:2:2		

	Sample/Pixel				
	1	2	3	4	5
Line	YC_bC_r	Y	Y	Y	YC_bC_r
	$\mathbf{YC_bC_r}$	**Y**	**Y**	**Y**	$\mathbf{YC_bC_r}$
	YC_bC_r	Y	Y	Y	YC_bC_r
	$\mathbf{YC_bC_r}$	**Y**	**Y**	**Y**	$\mathbf{YC_bC_r}$
			4:1:1		

	Sample/Pixel				
	1	2	3	4	5
Line	Y	Y	Y	Y	Y
	C_bC_r		C_bC_r		C_bC_r
	Y	**Y**	**Y**	**Y**	**Y**
	Y	Y	Y	Y	Y
	C_bC_r		C_bC_r		C_bC_r
	Y	**Y**	**Y**	**Y**	**Y**
			4:2:0		

Y = luminance sample; C_bC_r = chrominance samples; YC_bC_r = pixels so shown are co-sited. Boldfaced type indicates bottom field, if interlaced.

Waveform location	Voltage level	8-Bit Decimal Value	8-Bit Hox Value	8-Bit Binary Value	10-Bit Decimal Value	10-Bit Hox Value	10-Bit Binary Value
Excluded	766 .3 mV				1023	3FF	11 1111 1111
Excluded	763 .9 mV	255	FF	1111 1111	1020	3FF	11 1111 1100
Peak	700 .0 mV	235	EB	1110 1011	940	3AC	11 1010 1100
Black	0 .0 mV	16	10	0001 0000	64	040	00 0100 0000
Excluded	–48.7 mV				3	003	00 0000 0011
Excluded	–51.1 mV	0	0	0000 0000	0	000	00 0000 0000

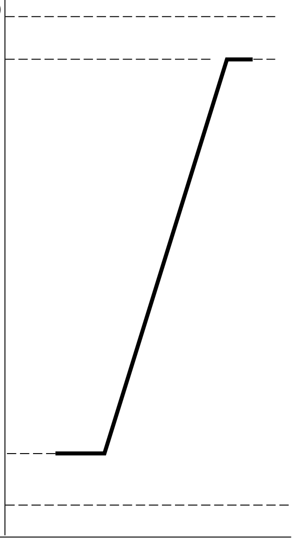


Figure 16.

Waveform location	Voltage level	8-Bit Decimal value	8-Bit Hex value	8-Bit Binary value	10-Bit Decimal value	10-Bit Hex value	10-Bit Binary value
Excluded	399.2 mV				1023	3FF	11 1111 1111
Excluded	396.9 mV	255	FF	1111 1111	1020	3FC	11 1111 1100
Max positive	350.0 mV	240	F0	1111 0000	960	3C0	11 1100 0000
Black	0.0 mV	128	80	1000 0000	512	200	10 0000 0000
Max negative	–350.0 mV	16	10	0001 0000	64	040	00 0100 0000
Excluded	–397.7 mV				3	003	00 0000 0011
Excluded	–400.0 mV	0	00	0000 0000	0	000	00 0000 0000

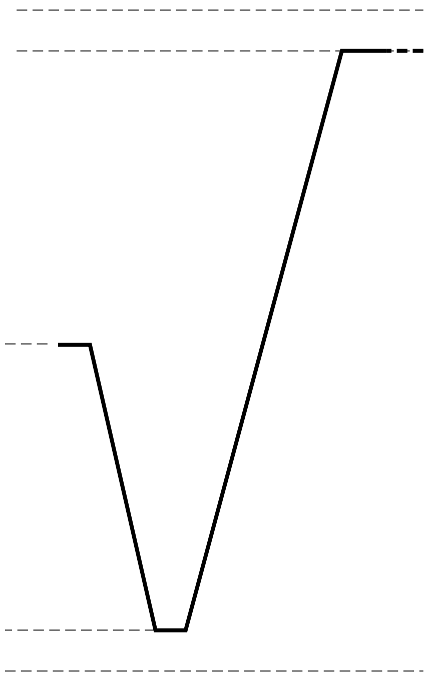


Figure 17. Quantizing levels for component digital color difference.

			8-Bit			10-Bit		
Waveform location	Voltage level	IRE units	Decimal value	Hex value	Binary value	Decimal value	Hex value	Binary value
Excluded	998.7 mV	139.8				1023	3FF	11 1111 1111
Excluded	994.9 mV	139.3	255	FF	1111 1111	1020	3FC	11 1111 1100
100% Chroma	907.7 mV	131.3	244	F4	1111 0100	975	3CF	11 1100 1111
Peak white	714.3 mV	100	200	C8	1100 1000	800	320	11 0010 0000
Blanking	0.0 mV	0	60	3C	0011 1100	240	0F0	00 1111 0000
Sync tip	–285.7 mV	–40	4	04	0000 0100	16	101	00 0001 0000
Excluded	–302.3 mV	–42.3				3	003	00 0000 0011
Excluded	–306.1 mV	–42.9	0	00	0000 0000	0	000	00 0000 0000

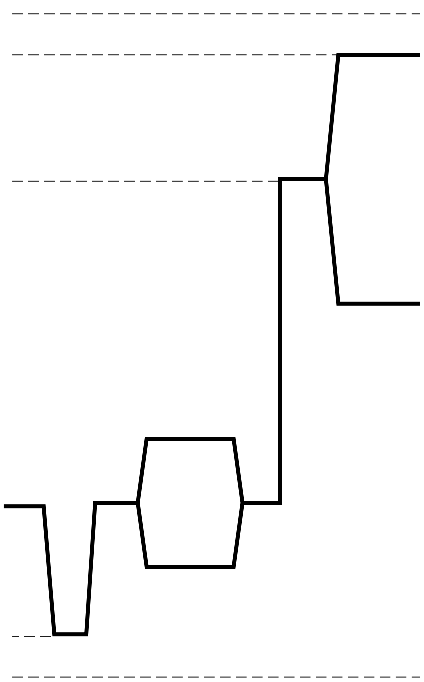


Figure 18. Quantizing levels for composite digital NTSC.

accommodate the 25 Hz offset in PAL, lines 313 and 625 each have 1137 samples. The active picture portion of a line consists of 768 samples in NTSC and 948 samples in PAL. These specifications are standardized as SMPTE 244M (NTSC) and EBU Tech. 3280 (PAL).

Unlike component digital, nearly the entire horizontal and vertical blanking intervals are sampled and quantized, which degrades the amplitude resolution (Fig. 18). However, in PAL, no headroom is provided for sync level, and the sampling instants are specified at 45° from the peak excursions of the V and U components of subcarrier (Fig. 19). This allows a "negative headroom" in the positive direction. Thus, an improvement of about 0.5 dB in signal-to-noise ratio is obtained.

Rate conversion between component and composite digital television signals involves different sampling points and quantizing levels. Each conversion degrades the picture, because exact levels cannot be reproduced in each pass. An important advantage of digital coding is thereby lost. In addition, decoding composite signals requires filtering to prevent cross-luminance and cross-color effects. This forever removes a part of the information; therefore, this process must be severely limited in its use.

Ancillary data may be added to digital component and composite video signals. AES/EBU-encoded digital audio can be multiplexed into the serial bit stream. Four channels are possible with the composite format, and 16 channels are possible with component digital video.

Component Video Standards

The video signals from a camera before encoding to NTSC, PAL, SECAM, or the ATSC Digital Standard are normally green (G), blue (B), and red (R). These are described as component signals because they are parts or components of the whole video signal. It has been found more efficient of bandwidth use for distribution and sometimes for processing to convert these signals into a luminance signal (Y), and two color-difference signals, blue minus luminance (B − Y) and red minus luminance (R − Y), where the color difference signals use $\frac{1}{2}$ or $\frac{1}{4}$ of the bandwidth of the luminance signal. The SMPTE/EBU Standard N10 has been adopted which has a uniform signal specification for all 525/60 and 625/50 television systems. The color difference signals in this standard, when they are digitally formatted, are termed C_b and C_r respectively. At the same time, due to the lower sensitivity of the human eye to fine detail in color, it is possible to reduce the bandwidth of the color difference signals compared to that of the luminance signal.

When these signals are digitized according to International Telecommunication Union, Radiocommunication Sector, (ITU-R) Recommendation 601, for both 525/60 and 625/50 systems, there are several modes of transmission which may be used, all based on multiples of a 3.75 MHz sampling rate. For the ATSC standard, 4:2:0 is used (see below and the ATSC digital television standard). Either 8, or more frequently 10 bits per sample are used.

		8-Bit			10-Bit		
Waveform location	Voltage level	Decimal value	Hex value	Binary value	Decimal value	Hex value	Binary value
Excluded	913.1 mV				1023	3FF	11 1111 1111
Excluded	909.5 mV	255	FF	1111 1111	1020	3FC	11 1111 1100
100% chroma Highest sample	886.2 mV	250	F4	1111 1010	1000	3E8	11 1110 1000
Peak white	700.0 mV	211	D3	1101 0011	844	34C	11 0100 1100
Blanking	0.0 mV	64	40	0100 0000	256	100	01 0000 0000
Sync tip	–300.0 mV	1	01	0000 0001	4	004	00 0000 0100
Excluded	–301.2 mV				3	003	00 0000 0011
Excluded	–304.8 mV	0	00	0000 0000	0	000	00 0000 0000

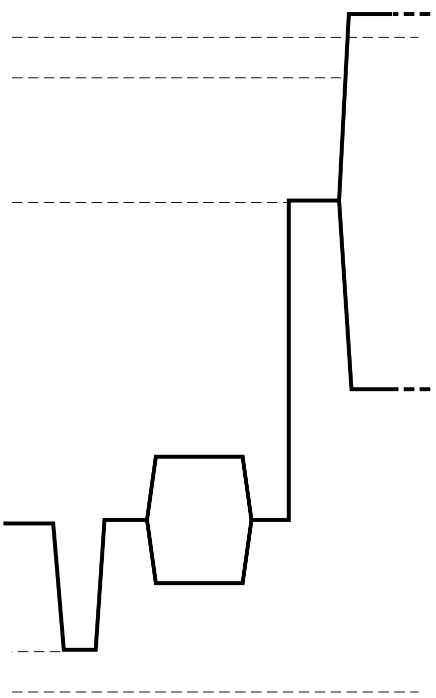


Figure 19. Quantizing levels for composite digital PAL.

4 : 4 : 4 Mode. The G, B, R or Y, C_b, C_r signal with an equal sampling rate of 13.5 MHz for each channel is termed the 4 : 4 : 4 mode of operation, and it yields 720 active samples per line for both 525/60 and 625/50 standards. This mode is frequently used for postproduction. If a (full-bandwidth) key signal is also required to be carried with the video, this combination is known as a 4 : 4 : 4 : 4 signal.

4 : 2 : 2 Mode. More frequently used for distribution is the 4 : 2 : 2 mode, where Y is sampled at 13.5 MHz, and the color difference signals are sampled at 6.25 MHz rate, corresponding to 360 active samples per line.

4 : 1 : 1 Mode. The 4 : 1 : 1 mode is used where bandwidth is at a premium, and the color difference signals are each sampled at 3.75 MHz rate, corresponding to 180 samples per line.

4 : 2 : 0 Mode. A further alternative, 4 : 2 : 0 mode, whose structure is not self evident, is derived from a 4 : 2 : 2 sampling structure, but reduces the vertical resolution of the color difference information by 2 : 1 to match the reduced color difference horizontal resolution. Four line (and field sequential if interlaced) co-sited C_b, C_r samples are vertically interpolated weighted toward the closest samples, and the resultant sample is located in between two adjacent scanning lines. This mode is used in MPEG bit-rate reduced digital signal distribution formats, and hence in the ATSC digital television standard.

The above four modes are illustrated in Table 6.

ADVANCED TELEVISION SYSTEMS, CURRENT AND FUTURE

ATSC Digital Television Standard

Overview. The Advisory Committee on Advanced Television Service (ACATS) to the Federal Communications Commission, with support from Canada and Mexico, from 1987 to 1995 developed a recommendation for an Advanced Television Service for North America. The ACATS enlisted the cooperation of the best minds in the television industry, manufacturers, broadcasters, cable industry, film industry, and federal regulators in its organization to develop an advanced television system which would produce a substantial improvement in video images and in audio performance over the existing NTSC, 525-line system. The primary video goal was at least a doubling of horizontal and vertical resolution with a widening in picture aspect ratio from current 4 (W) × 3 (H) to 16 (W) × 9 (H), and this was named “high-definition television.” Also included was a digital audio system consisting of five channels plus a low-frequency channel (5.1).

Twenty-one proposals were made for terrestrial transmission systems for extended-definition television (EDTV) or high-definition television (HDTV), using varying amounts of RF spectrum. Some systems augmented the existing NTSC system, with an additional channel of 3 MHz or 6 MHz, some used a separate simulcast channel of 6 MHz or 9 MHz bandwidth, and all of the early systems used hybrid analog/digital technology in the signal processing with an analog RF transmission system. Later proposals changed the RF transmission system to digital along with all-digital signal processing.

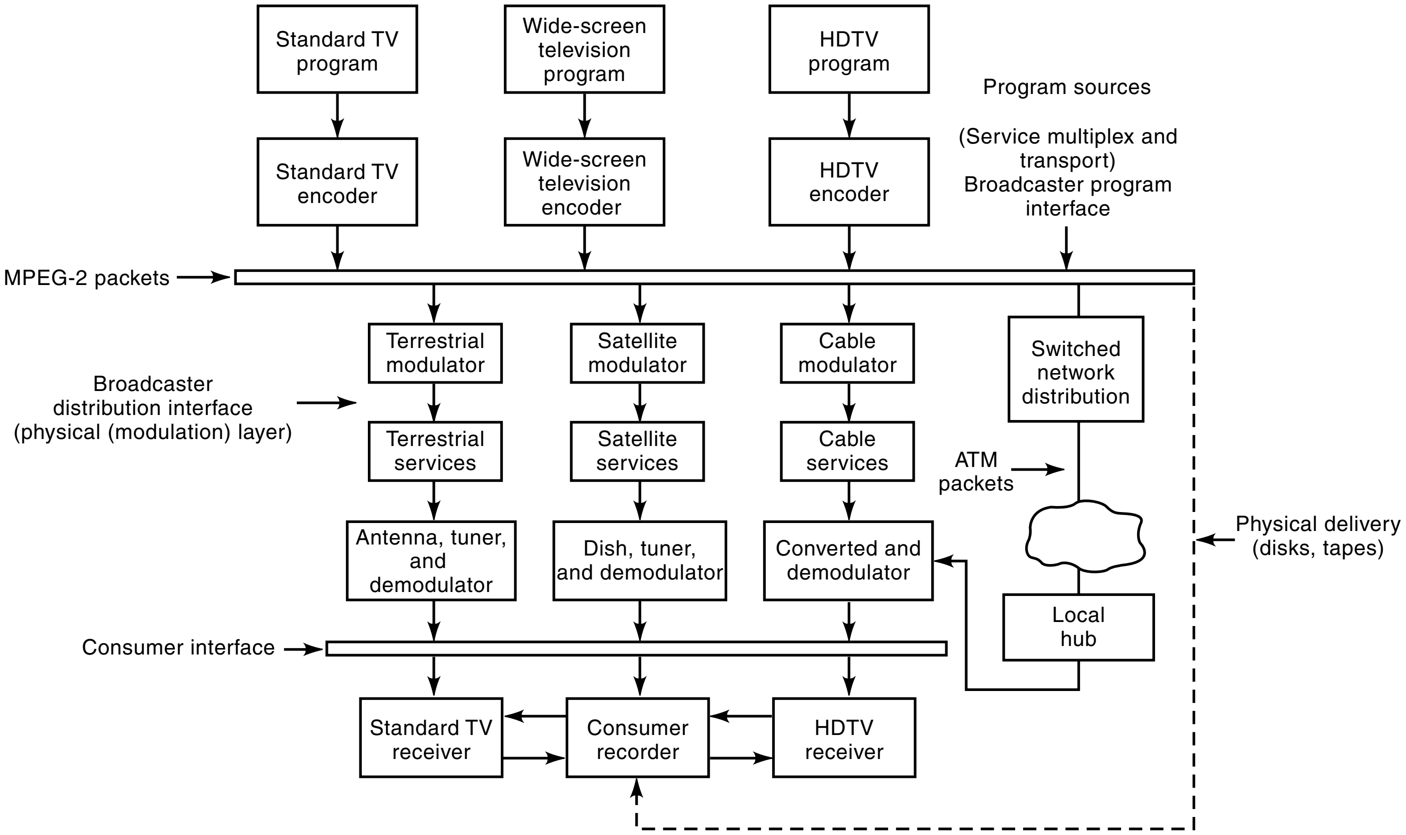


Figure 20. Television service model.

It was also decided that the signal would be transmitted in a 6 MHz RF channel, one for each current broadcaster of the (6 MHz channel) NTSC system, and that this new channel would eventually replace the NTSC channels. The additional channels were created within the existing UHF spectrum by improved design of TV receivers so that the previously taboo channels, of which there were many, could now be used.

In parallel with this effort, the Advanced Television Systems Committee (ATSC) documented and developed the standard known as the ATSC Digital Television Standard, and it is subsequently developing related implementation standards.

In countries currently using 625-line, 4 : 3 aspect ratio television systems, plans are being developed to eventually use a 1250-line, 16 : 9 aspect ratio system, and the ITU-R has worked successfully on harmonizing and providing interoperability between the ATSC and 1250-line systems.

Figure 20 shows the choices by which the signals of the various television standards will reach the consumer. Other articles detail satellite, cable TV, and asynchronous transfer mode (ATM) common carrier networks.

The ATSC and the ITU-R have agreed on a digital terrestrial broadcasting model, which is shown in Fig. 21. Video and audio sources are coded and compressed in separate video and audio subsystems. The compressed video and audio are then combined with ancillary data and control data in a service multiplex and transport, in which form the combined signals are distributed to the terrestrial transmitter. The signal is then channel-coded, modulated, and fed at appropriate power to the transmission antenna. The receiver reverses the process, demodulating the RF signal to the transport stream, then demultiplexing the audio, video, ancillary, and control data into their separate but compressed modes, and the individual subsystems then decompress the bit streams into video and audio signals which are fed to display screen and speakers, and the ancillary and control data are used if and as appropriate within the receiver.

Information Service Multiplex and Transport System. These subsystems provide the foundation for the digital communication system. The raw digital data are first formatted into *elementary bit streams,* representing image data, sound data and ancillary data. The elementary bit streams are then formed into manageable packets of information (*packetized elementary stream,* PES), and a mechanism is provided to indicate the start of a packet (synchronization) and assign an appropriate identification code (*packet identifier,* PID) within a header to each packet. The packetized data are then multiplexed into a *program transport stream* which contains all the information for a single (television) program. Multiple program transport streams may then be multiplexed to form a *system level multiplex transport stream.*

Figure 22 illustrates the functions of the multiplex and transport system and shows its location between the application (e.g., audio or video) encoding function and the transmission subsystem. The transport and demultiplex subsystem

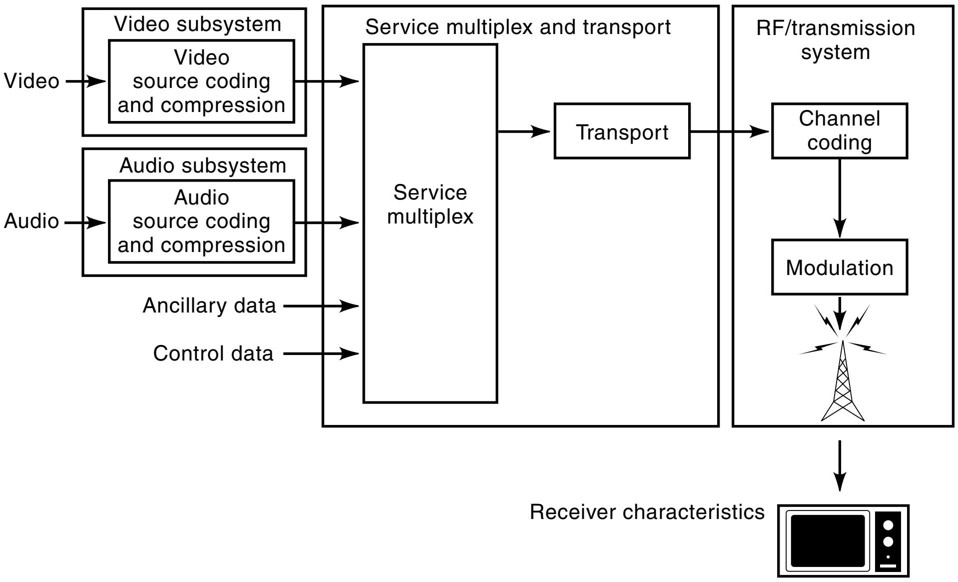


Figure 21. Block diagram showing ATSC and ITU-R terrestrial television broadcasting model.

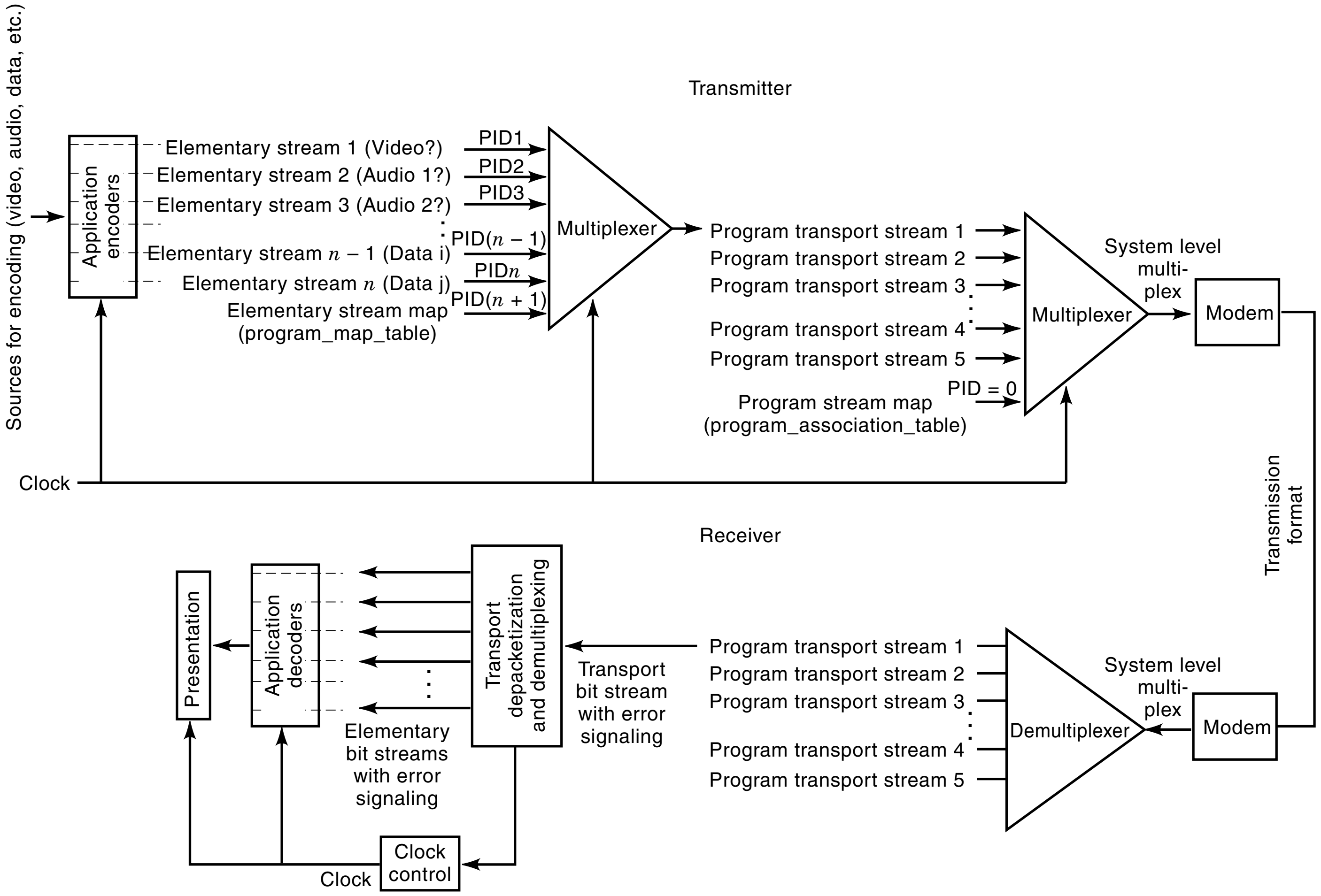


Figure 22. Organization of functionality within a transport system for digital TV programs.

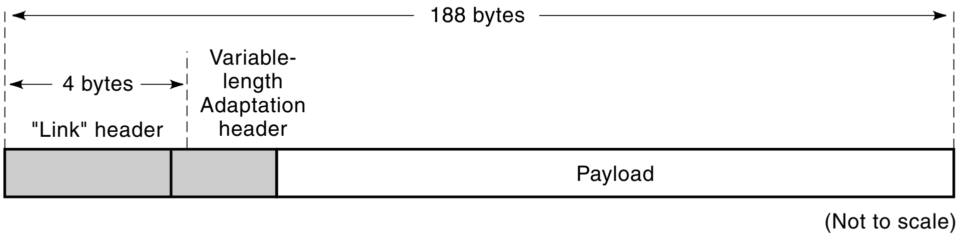


Figure 23. Transport packet format.

functions in the receiver in the reverse manner, being situated between the RF modem and the individual application decoders.

Fixed-Length Packets. The transport system employs the fixed-length transportation stream packetization approach defined by the Moving Picture Experts Group (MPEG), which is well-suited to the needs of terrestrial broadcast and cable television transmission of digital television. The use of moderately long, fixed-length packets matches well with the needs for error protection, and it provides great flexibility for initial needs of the service to multiplex audio, video, and data, while providing backward compatibility for the future and maximum interoperability with other media (MPEG-based).

Packet Identifier. The use of a PID in each packet header to identify the bit stream makes it possible to have a mix of audio, video, and auxiliary data which is not specified in advance.

Scalability and Extensibility. The transport format is scalable in that more elementary bit streams may be added at the input of the multiplexer, or at a second multiplexer. Extensibility for the future could be achieved with no hardware modification by assigning new PIDs for additional elementary bit streams.

Robustness. After detecting errors during transmission, the data bit stream is recovered starting with the first good packet. This approach ensures that recovery is independent of the properties of each elementary bit stream.

Transport Packet Format. The data transport packet format, as shown in Fig. 23, is based on fixed length packets (188 bytes) identified by a variable-length header including a sync byte and the PID. Each header identifies a particular application bit stream (elementary bit stream) which forms the payload of the packet. Applications include audio, video, auxiliary data, program and system control information, and so on.

PES Packet Format. The elementary bit streams are themselves wrapped in a variable-length packet structure called the packetized elementary stream (PES) before transport processing. See Fig. 24. Each PES packet for a particular elementary bit stream then occupies a variable number of transport packets, and data from the various elementary bit streams are interleaved with each other at the (fixed length) transport packet layer. New PES packets always start a new transport packet, and stuffing bytes (i.e., null bytes) are used to fill partially filled transport packets.

Channel Capacity Allocation. The entire channel capacity can be reallocated to meet immediate service needs. As an example, ancillary data can be assigned fixed amounts depending on a decision made as to how much to allocate to video; or if the data transmission time is not critical, then it can be sent as *opportunistic data* during periods when the video channel is not fully loaded.

Figure 25 illustrates how the variable-length PES packets relate to the fixed-length transport packets.

The transport system provides other features, including decoder synchronization, conditional access, and local program insertion. Also issues relating to the storage and playback of programs are addressed, and the appropriate hooks are provided to support the design of consumer digital products based on recording and playback of these bitstreams, including the use of “trick modes” such as slow motion and still frame, typical of current analog video cassette recorders (VCRs).

Local Program Insertion. This feature is extremely important to permit local broadcast stations to insert video, audio, or data which is unique to that station. As shown in Fig. 26 to splice local programs, it is necessary to extract (by demultiplexing) the transport packets, identified by the PIDs of the individual elementary bit streams, which make up the program that is to be replaced, including the *program map table,* which identifies the individual bit streams that make up the program. Program insertion can then take place on an individual PID basis, using the fixed-length transport packets.

Presentation Time Stamp and Decoding Time Stamp. These time stamps both occur within the header of the PES packet, and they are used to determine when the data within the packet should be read out of the decoder. This process ensures the correct relative timing of the various elementary streams

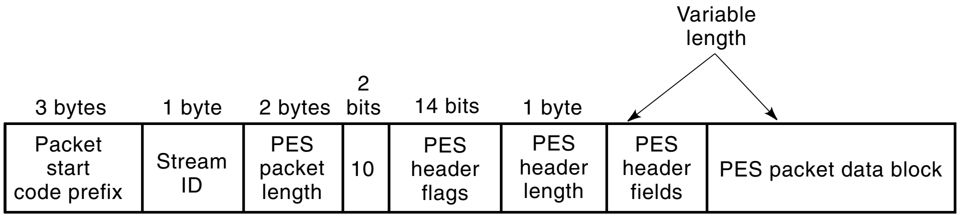


Figure 24. Structural overview of packetized elementary stream (PES) packet.

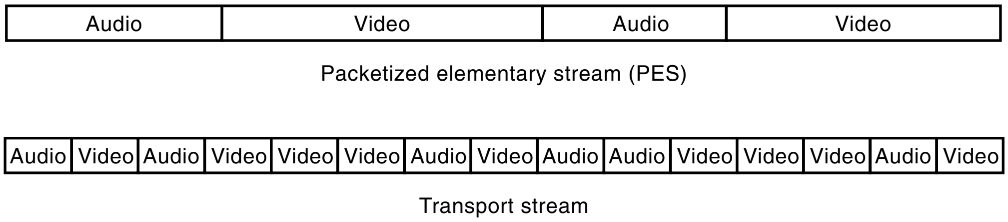


Figure 25. Variable-length PES packets and fixed-length transport packets.

at the decoder relative to the timing at which they were encoded.

Interoperability with ATM. The MPEG-2 transport packet size (188 bytes) is such that it can easily be partitioned for transfer in a link layer which supports asynchronous transfer mode (ATM) transmission (53 bytes per cell). The MPEG-2 transport layer solves MPEG-2 presentation problems and performs the multimedia multiplexing function, while the ATM layer solves switching and network adaptation problems.

Video Systems

Compressed Video. Compression in a digital HDTV system is required because the bit rate required for an uncompressed HDTV signal approximates 1 Gbps (with the luminance/chrominance sampling already compressed to 4 : 2 : 2 mode). The total transmitted data rate in the ATSC digital television standard over a 6 MHz channel is approximately 19.4 Mbps. A compression ratio of 50 : 1 or greater is therefore required.

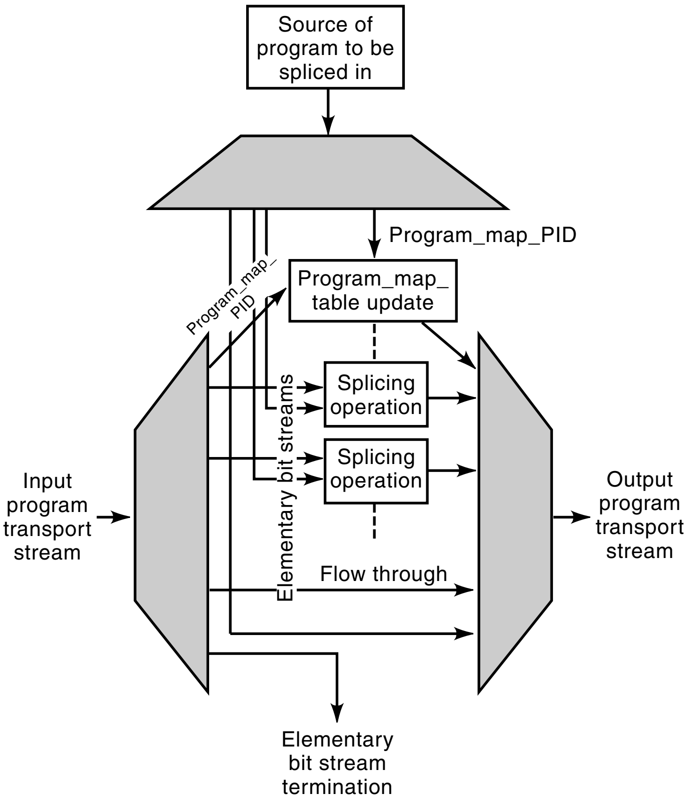


Figure 26. Example of program insertion architecture.

The ATSC Digital Television Standard specifies video compression using a combination of compression techniques which for compatibility conform to the algorithms of MPEG-2 Main Profile, High Level.

The goal of the compression and decompression process is to produce an approximate version of the original image sequence, such that the reconstructed approximation is imperceptibly different from the original for most viewers, for most images, and for most of the time.

Production Formats. A range of production format video inputs may be used. These include the current NTSC format of 483 active lines, 720 active samples/line, 60 fields, 2 : 1 interlaced scan (60I), the Standard Definition format of 480 active lines, 720 active samples/line, 60 frames progressive scan (60P), and high definition formats of 720 active lines, 1280 active samples/line, 60P, or 1080 active lines, 1920 active samples/line, 60I.

Compression Formats. A large range of 18 compression formats is included, to accommodate all of the above production formats. The 30P and 24P formats are included primarily to provide efficient transmission of film images, associated with the above production formats. The VGA Graphics format is also included at 480 lines and 640 pixels (see below for pixel definition). Details of these compression formats are found in Table 7.

Colorimetry. The Digital Television Standard specifies SMPTE 274M colorimetry (same as ITU-R BT.709, 1990) as the default, and preferred, colorimetry. This defines the color primaries, transfer characteristics, and matrix coefficients.

Sample Precision. After preprocessing, the various luminance and chrominance samples will typically be represented using 8 bits per sample of each component.

Film Mode. In the case of 24 fps film which is sent at 60 Hz rate using a 3 : 2 pull-down operation, the processor may detect the sequences of three nearly identical pictures followed by two nearly identical pictures and may only encode the 24 unique pictures per second that existed in the original film sequence. This avoids sending redundant information, and permits higher quality transmission. The processor may detect similar sequencing for 30 fps film and may only encode the 30 unique pictures per second.

Table 7. ATSC Compression Formats: A Hierarchy of Pixels and Bits

Active Lines	Pixels per Line	Total Pixels per Frame	Uncompressed Payload Bit Rate in Mbps (8-bit 4 : 2 : 2 sampling) at Picture (Frame) Rate				Aspect Ratio and Notes
			60P	60I	30P	24P	
1080	1920	2,073,600	Future	995	995	796	16 : 9 only
720	1280	921,600	885	—	442	334	16 : 9 only
480	704	337,920	324	162	162	130	16 : 9 & 4 : 3
480	640	307,200	295	148	148	118	4 : 3 only (VGA)
Vertical	Horizontal		Higher	← →		Lower	
Resolution			Temporal Resolution				

Source: Data courtesy of Patrick Griffis, Panasonic, NAB, 1998.

Color Component Separation and Processing. The input video source to the video compression system is in the form of RGB components matrixed into luminance (Y) (intensity or black-and-white picture) and chrominance (C_b and C_r) color-difference components, using a linear transformation. The Y, C_b, and C_r signals have less correlation with each other than R, G, and B and are thus easier to code. The human visual system is less sensitive to high frequencies in the chrominance components than in the luminance components. The chrominance components are low-pass-filtered and subsampled by a factor of two in both horizontal and vertical dimensions (4 : 2 : 0 mode) (see section entitled “Component Video Standards”).

Representation of Picture Data. Digital television uses digital representation of the image data. The process of digitization involves sampling of the analog signals and their components, in a sequence corresponding to the scanning raster of the television format, representing each sample with a digital code.

Pixels. The individual samples of digital data are referred to as picture elements, or “pixels” or “pels.” When the ratio of active pixels per line to active pixels per frame is the same as the aspect ratio, the format is said to have “square pixels.” The term refers to the spacing of samples, not the shape of the pixel.

Blocks, Macroblocks, and Slices. For further processing, pixels are organized into blocks of 8 × 8, representing either luminance or chrominance information. Macroblocks consist of four blocks of luminance (Y) and one each of C_b and C_r. Slices consist of one or more macroblocks in the same row, and they begin with a slice start code. The number of slices affects compression efficiency; a larger number of slices provides for better error recovery, but uses bits that could otherwise be used to improve picture quality. The slice is the minimum unit for resynchronization after an error.

Removal of Temporal Information Redundancy: Motion Estimation and Compensation. A video sequence is a series of still pictures shown in rapid succession to give the impression of continuous motion. This usually results in much temporal redundancy (picture sameness) among the adjacent pictures. Motion compensation attempts to delete this temporal redundancy from the information transmitted. In the standard, the current picture is predicted from the previously encoded picture, estimating the motion between the two adjacent pictures and compensating for the motion. This “motion-compensated residual” is encoded rather than the complete picture, eliminating repetition of the redundant information.

Pictures, Groups of Pictures, and Sequences. The primary coding unit of a video sequence is the individual video frame or picture, which consists of the collection of slices constituting the active picture area. A video sequence consists of one or more consecutive pictures; and it commences with a sequence header, which can serve as an entry point.

One or more pictures or frames in sequence may be combined into a group of pictures (GOP), optional within MPEG-2 and the ATSC Standard, to provide boundaries for interpicture coding and registration of time code.

Figure 27 illustrates a time sequence of video frames consisting of intracoded pictures (I-frames), predictive coded pictures (P-frames), and bidirectionally predictive coded pictures (B-frames).

I-, P-, and B-Frames. Frames that do not use any interframe coding are referred to as I-frames (where I denotes intraframe coded). All the information for a complete image is contained within an I-frame, and the image can be displayed without reference to any other frame. (The preceding frames may not be present or complete for initialization or acquisition and the

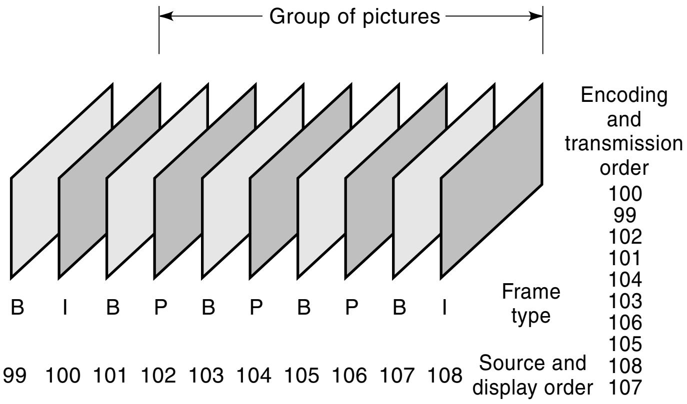


Figure 27. Video frame order, group of pictures, and typical I-frames, P-frames, and B-frames.

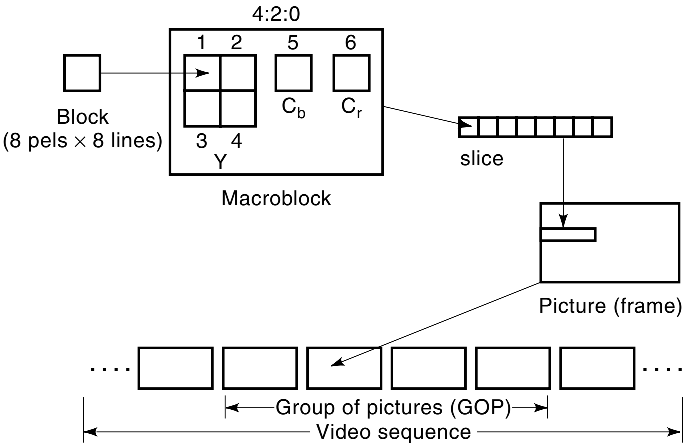


Figure 28. Video structure hierarchy.

preceding or following frames may not be present or complete when noncorrectable channel errors occur.)

P-frames (where P denotes predicted) are frames where the temporal prediction is in the forward direction only (formed only from pixels in the most recently decoded I- or P-frame). Interframe coding techniques improve the overall compression efficiency and picture quality. P-frames may include portions that are only intraframe-coded.

B-frames (where B denotes bidirectionally predicted) include prediction from a future frame as well as from a previous frame (always I- or P-frames). Some of the consequences of using future frames in the prediction are as follows: The transmission order of frames is different from the displayed order of frames, and the encoder and decoder must reorder the video frames, thus increasing the total latency. B-frames are used for increasing compression efficiency and perceived picture quality.

Figure 28 illustrates the components of pictures as discussed above.

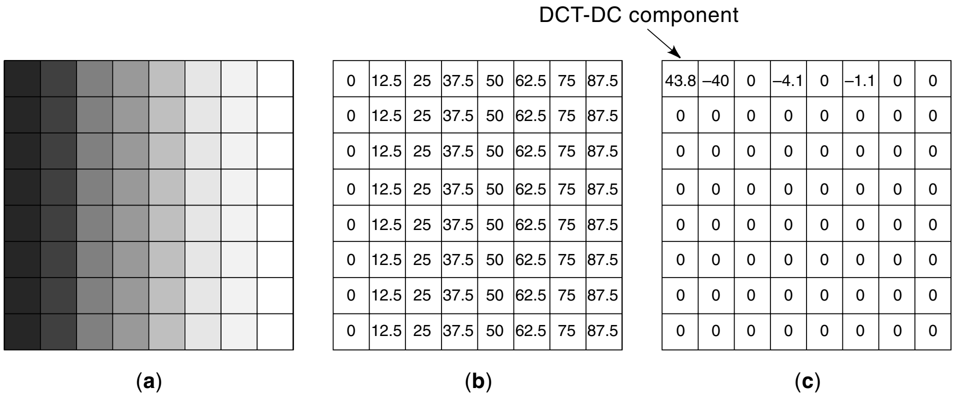
Removal of Spatial Information Redundancy: The Discrete Cosine Transform. As shown in Fig. 29, 8 × 8 blocks of spatial intensity showing variations of luminance and chrominance pel information are converted into 8 × 8 arrays of coefficients relating to the spatial frequency content of the original intensity information. The transformation method used is the Discrete Cosine Transform (DCT).

As an example, in Fig. 29(a), an 8 × 8 pel array representing a black to white transition is shown as increasing levels of a gray scale. In Fig. 29(b), the gray-scale steps have been digitized, and are represented by pel amplitude numerical values. In Fig. 29(c), the gray-scale block is represented by its frequency transformation coefficients, appropriately scaled. The DCT compacts most of the energy into only a small number of the transform coefficients. To achieve a higher decorrelation of the picture content, two-dimensional (along two axes) DCT coding is applied. The (0,0) array position (top left), represents the DC coefficient or average value of the array.

Quantizing the Coefficients. The goal of video compression is to maximize the video quality for a given bit rate. Quantization is a process of dividing the coefficients by a value of *N*, which is greater than 1, and rounding the answer to the nearest integer value. This allows scaling the coefficient values according to their importance in the overall image. Thus high-resolution detail to which the human eye is less sensitive may be more heavily scaled (coarsely coded). The quantizer may also include a dead zone (enlarged interval around zero) to core to zero small noise-like perturbations of the element value. Quantization in the compression algorithm is a lossy step (information is discarded which cannot be recovered).

Variable Length Coding, Codeword Assignment. The quantized values could be represented using fixed-length codewords. However, greater efficiency can be achieved in terms of bit rate, by employing what is known as Entropy Coding. This attempts to exploit the statistical properties of the signal to be encoded. It is possible to assign a shorter codeword to those values occurring more frequently and a longer codeword to those occurring less frequently. The Morse code is an example of this method. One optimal codeword design method, the Huffman Code, is used in the Standard. It will be noted that many zero value coefficients are produced, and these may be prioritized into long runs of zeros by zigzag scanning or a similar method.

Channel Buffer. Motion compensation, adaptive quantization, and variable-length coding produce highly variable amounts of compressed video data as a function of time. A buffer is used to regulate the variable-input bit rate into a



0	12.5	25	37.5	50	62.5	75	87.5
0	12.5	25	37.5	50	62.5	75	87.5
0	12.5	25	37.5	50	62.5	75	87.5
0	12.5	25	37.5	50	62.5	75	87.5
0	12.5	25	37.5	50	62.5	75	87.5
0	12.5	25	37.5	50	62.5	75	87.5
0	12.5	25	37.5	50	62.5	75	87.5
0	12.5	25	37.5	50	62.5	75	87.5

43.8	−40	0	−4.1	0	−1.1	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

(a) (b) (c)

Figure 29. Discrete cosine transform.

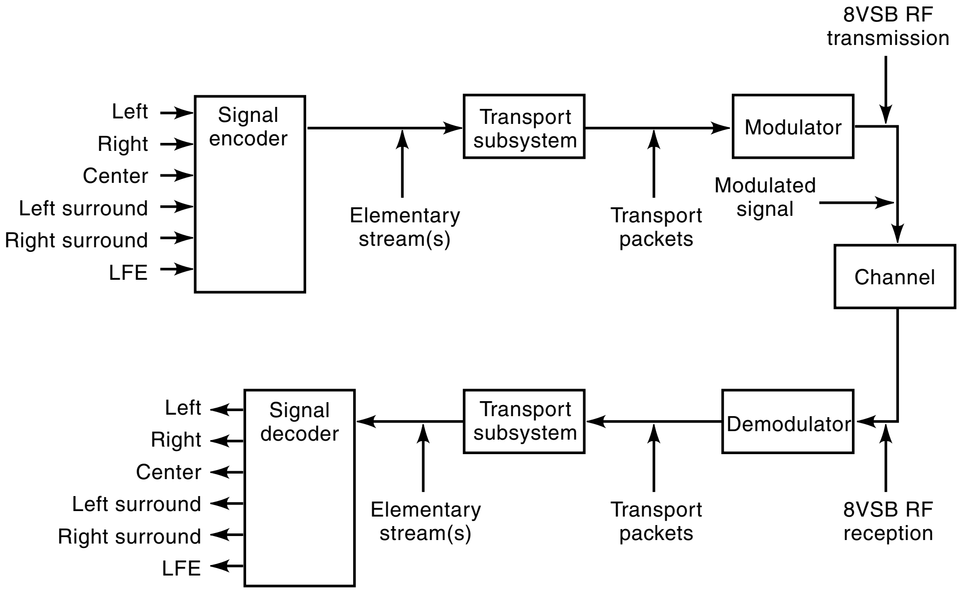


Figure 30. Audio subsystem within the digital television system.

fixed-output bit rate for transmission. The fullness of the buffer is controlled by adjusting the amount of quantization error in each image block (a rate controller driven by a buffer state sensor adjusts the quantization level). Buffer size is constrained by maximum tolerable delay through the system and by cost.

Audio

System Overview. The audio subsystem used in the ATSC Digital Television Standard is based on the AC-3 digital audio compression standard. The subsystem can encode from 1 to 6 channels of source audio from a pulse-code modulation (PCM) representation (requiring 5.184 Mbps for the 5.1 channel mode) into a serial bit stream at a normal data rate of 384 kbps. The 5.1 channels are left (front), center (front), right (front), left surround (rear), right surround (rear) (all 3 Hz to 20 kHz), and low-frequency subwoofer (normally placed centrally) (which represents the 0.1 channel, 3 Hz to 120 Hz). The system conveys digital audio sampled at a frequency of 48 kHz, locked to the 27 MHz system clock.

In addition to the 5.1 channel input, monophonic and stereophonic inputs and outputs can be handled. Monophonic and stereophonic outputs can also be derived from a 5.1 channel input, permitting backward compatibility.

The audio subsystem, as illustrated in Fig. 30, comprises the audio encoding/decoding function and resides between the audio inputs/outputs and the transport system. The audio encoder(s) is (are) responsible for generating the *audio elementary stream(s)*, which are encoded representations of the baseband audio input signals.

The transport subsystem packetizes the audio data into PES packets which are then further packetized into (fixed length) transport packets. The transmission subsystem converts the transport packets into a modulated RF signal for transmission to the receiver. Transport system flexibility allows multiple audio elementary streams to be transmitted. In the receiver, the encoding, packetization, and modulation process is reversed to produce reconstructed audio.

Audio Compression. Two mechanisms are available for reducing the bit rate of sound signals. The first utilizes statistical correlation to remove redundancy from the bit stream. The second uses the psychoacoustical characteristics of the human hearing system such as spectral and temporal masking to reduce the number of bits required to recreate the original sounds.

The audio compression system consists of three basic operations, as shown in Fig. 31. In the first stage, the representation of the audio signal is changed from the time domain to the frequency domain, which is more efficient in order to perform psychoacoustically based audio compression. The frequency domain coefficients may be coarsely quantized because the resulting quantizing noise will be at the same frequency as the audio signal, and relatively low signal-to-noise ratios (SNRs) are acceptable due to the phenomena of psychoacoustic masking. The bit allocation operation determines what actual SNR is acceptable for each individual frequency coefficient. Finally, the frequency coefficients are coarsely quantized to the necessary precision and formatted into the audio elementary stream.

The basic unit of encoded audio is the AC-3 sync frame, which represents six audio blocks of 256 frequency coefficient samples (derived from 512 time samples), a total of 1536 samples. The AC-3 bit stream is a sequence of AC-3 sync frames.

Additional Audio Services. Additional features are provided by the AC-3 subsystem. These include loudness normalization, dynamic range compression with an override for the listener, and several associated services, namely, dialogue, commentary, emergency, voice-over, help for the visually impaired and hearing-impaired (captioning), and multiple languages. Some of these services are mutually exclusive, and multilanguage service requires up to an extra full 5.1 channel service for each language (up to an additional 384 kbps).

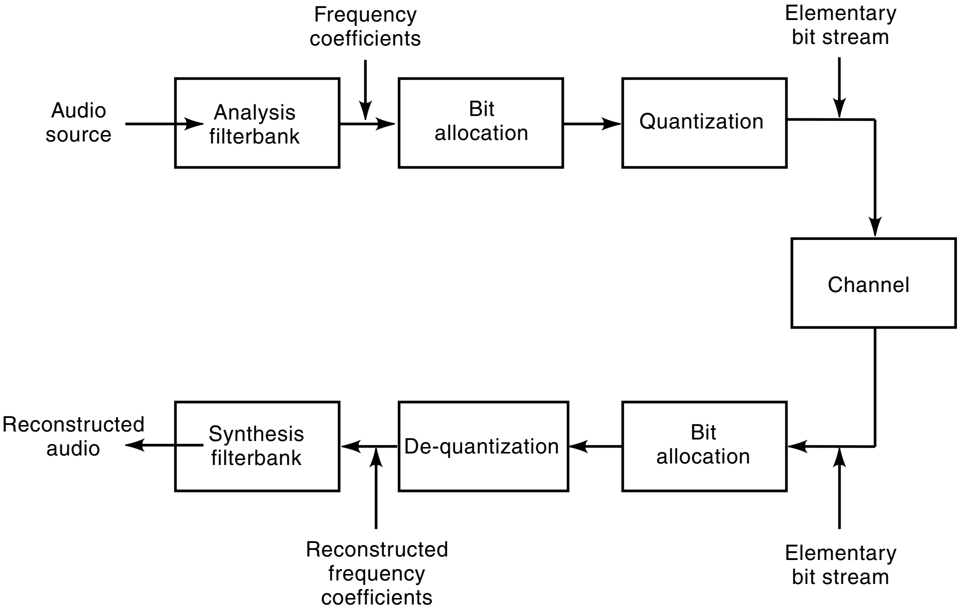


Figure 31. Overview of audio compression system.

Ancillary Data Services

Several data services have been included in the ATSC Standard. Other services can be added in the future. Currently included are program subtitles (similar to closed captioning in NTSC), emergency messages (mixed into baseband video in NTSC), and program guide information.

Possible Future Data Services. Information data related to the following may be desired: conditional access, picture structure, colorimetry, scene changes, local program insertion, field/frame rate and film pull-down, pan/scan, multiprogram, and stereoscopic image.

Transmission Characteristics. The transmission subsystem uses a vestigial sideband (VSB) method: (1) 8-VSB for simulcast terrestrial broadcast mode and (2) a 16-VSB high data rate mode. VSB includes a small part of the lower sideband with the full upper sideband. Sloped filtering at the transmitter and/or the receiver attenuates the lower end of the band. The 8-VSB coding maps three bits into one of eight signal levels. The system uses a symbol rate of 10.76 Msymbols/s, capable of supporting a data stream payload of 19.39 MBits/s. See Fig. 32 VSB in 6-MHz channel.

Modulation techniques for some other planned broadcast systems use orthogonal frequency division multiplexing (OFDM) or coded OFDM (COFDM), which is a form of multicarrier modulation where the carrier spacing is selected, so that each subcarrier within the channel is orthogonal to the other subcarriers, which mathematically ensures that during the sampling time for one carrier, all other carriers are at a zero point.

The 8-VSB subsystem takes advantage of a pilot, segment sync, and a training sequence for robust acquisition and operation. In order to maximize service area, an NTSC rejection filter (in the receiver) and trellis coding are used. The system can operate in a signal-to-additive-white-Gaussian noise (S/N) environment of 14.9 dB. The transient peak power to average power ratio as measured on a low-power transmitted signal with no nonlinearities is no more than 6.3 dB for 99.9% of the time.

A block diagram of a generic transmitter subsystem is shown in Fig. 33. The incoming data (19.39 MB/s) is randomized and then processed for forward error correction (FEC) in the form of Reed–Solomon coding (20 RS parity bits are added to each packet, known as outer error correction). Data interleaving, to reorganize the data stream so that it is less vulnerable to bursts of errors, then interleaves to a depth of about $\frac{1}{6}$ data field (4 ms deep).

The second stage, called inner error correction, consists of a $\frac{2}{3}$ rate trellis coding. This encodes one bit of a two-bit pair into two output bits, using a $\frac{1}{2}$ convolutional code, whereas the other input bit is retained as precoded. Along with the Trellis Encoder, the data packets are precoded into Data Frames and mapped into a signaling waveform using an 8-level (3 bit), one-dimensional constellation (8 VSB). Data Segment Sync (4

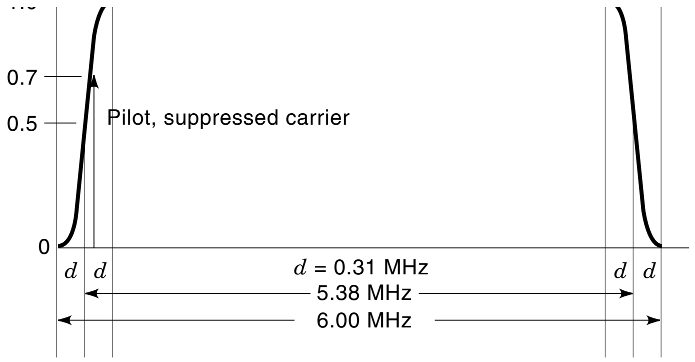


Figure 32. Vestigial sideband (VSB) in 6 MHz channel for digital transmission.

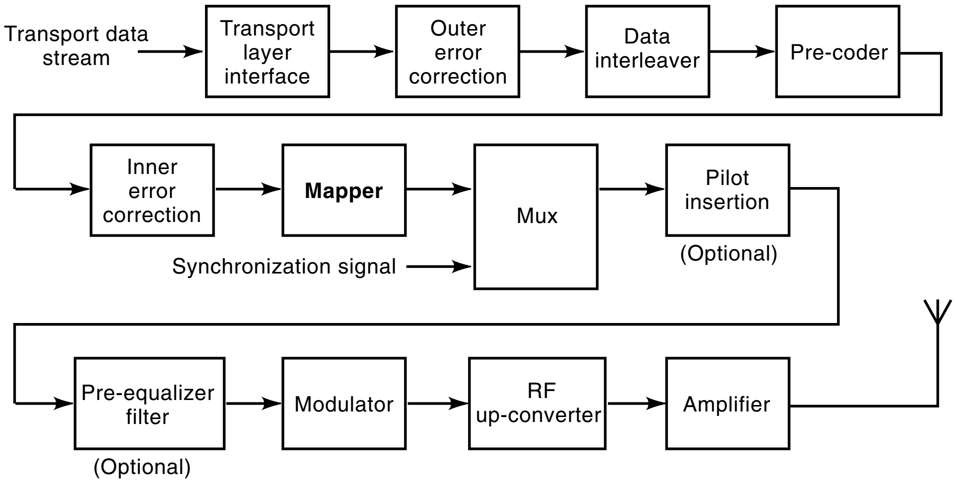


Figure 33. 8-VSB transmitter subsystem block diagram.

symbols = 1 byte) at the beginning of a segment of 828 data plus parity symbols, and Data Field Sync at the beginning of a Data Field of 313 segments (24.2 ms), are then added. Data Field Sync includes the training signal, used for setting the receiver equalizer.

A small in-phase pilot is then added to the data signal at a power of 11.3 dB below the average data signal power. The data is then modulated onto an IF carrier, which is the same frequency for all channels. The RF Up-Converter then translates the filtered, flat IF data signal spectrum to the desired RF channel. It is then amplified to the appropriate power for the transmitting antenna.

For the same approximate coverage as an NTSC transmitter (at the same frequency), the average power of the ATV signal is approximately 12 dB less than the NTSC peak sync power.

The frequency of the RF upconverter oscillator will typically be the same as for NTSC (except for offsets). For extreme co-channel situations, precise RF carrier frequency offsets with respect to the NTSC co-channel carrier may be used to reduce interference into the ATV signal. The ATV signal is noise-like, and its interference into NTSC does not change with precise offset.

The ATV co-channel pilot should be offset in the RF upconverter from the dominant NTSC picture carrier by an odd multiple of half the data segment rate. An additional offset of 0, +10 kHz, or −10 kHz is required to track the principal NTSC interferer.

For ATV-into-ATV co-channel interference, precise carrier offset prevents the adaptive equalizer from misinterpreting the interference as a ghost.

The Japanese High-Definition Television Production System

This television production system was developed by the Japanese Broadcasting Corporation (NHK). It was standardized in 1987 by the Broadcast Technology Association (BTA), now renamed the Association of Radio Industries and Business (ARIB), in Japan and in the United States by SMPTE (240M and 260M Standards). It uses a total of 1125 lines (1035 active lines), is interlaced at a field rate of 60 Hz, and has an aspect ratio of 16 : 9. It requires a bandwidth of 30 MHz for the luminance signal (Y), and 15 MHz for each of the two color difference signals (P_B and P_R). When digitized at 8 bits per sample, it uses 1920 pixels per line and it requires a total bit rate of 1.2 Gbps. Note that this production system is similar to the interlaced system used in the ATSC standard, except that the latter uses 1080 active lines.

Japanese MUSE Transmission Systems

A range of transmission systems were developed by NHK based on the Multiple Sub-Nyquist Encoding (MUSE) transmission scheme (see Table 8). MUSE (8.1 MHz bandwidth) was developed for DBS broadcasting and MUSE-T (16.2 MHz bandwidth) was developed for satellite transmission. MUSE-6 was designed to be compatible with a 6 MHz channel and NTSC receivers. MUSE-9 uses a 3 MHz augmentation channel in addition to the standard 6 MHz channel and is NTSC receiver-compatible.

Japanese Hi-Vision System

This system incorporates the 1920 × 1035 television production system and the MUSE-E transmission system. MUSE-E uses an 8.1 MHz bandwidth, and is incompatible with standard NTSC receivers and channel allocations. Four audio channels are time-division-multiplexed with the video signals, in the blanking intervals. The encoding and decoding processes are both very complex and require many very large scale integration (VLSI) chips. This system requires a MUSE-E receiver, or a set-top box equipped with a MUSE decoder feeding either a 16 : 9 display or a 4 : 3 aspect ratio conventional receiver. In the near-term, NHK will use simultaneous Hi-Vision/NTSC program production.

The MUSE systems are not receiver-compatible with either the North-American ATSC system or the European DVB system (see below).

The Japanese Enhanced Definition Television System (EDTV-II)

EDTV-II is an NTSC-compatible letter-box analog transmission system standardized by the ARIB in Japan. The input signal is 525 line, 60-frame progressive scan (525P) with 16 : 9 aspect ratio. 525-line, 30-frame interlaced scan (525I) can be

Table 8. MUSE Transmission Systems

Transmission System	Type of Transmission	Bandwidth	Channel Compatible	Compatible with NTSC
MUSE	Direct Broadcast by Satellite (DBS)	8.1 MHz	NA	No
MUSE-T	Satellite	16.2 MHz	NA	No
MUSE-6	Terrestrial Broadcast	6 MHz	Yes	Yes
MUSE-9	Terrestrial Broadcast	6 + 3 MHz Augmentation	Yes, with 2nd 3 MHz channel	Yes
MUSE-E	Terrestrial Broadcast	8.1 MHz	No	No

upconverted as an input signal. Note that the 525P signal is one of the SDTV signal formats defined in the ATSC Standard (720 × 480 at 60P). It is also defined as a production format in SMPTE 293M and SMPTE 294M standards documents.

Compared with the current 525I standard, the frame rate has been doubled from 30 to 60. The sampling frequency in the format has been doubled to 27 MHz, compared to 525I, and the aspect ratio has been changed from 4 : 3 to 16 : 9. This increase of sampling frequency permits comparable resolution in H and V axes to be maintained. The production system is effectively an 8 : 4 : 4 digital system with production interfaces at 540 Mbps. 4 : 2 : 0 can also be used in production and would require interfacing at 360 Mbps. Horizontal blanking is shrunk to achieve this bit rate.

The EDTV-II analog transmission system is used for both terrestrial and satellite broadcasting. It requires the same bandwidth as the NTSC system and no changes are needed in transmitter implementations. The image is displayed on an EDTV-II receiver in a progressive manner with 480 lines and 16 : 9 aspect ratio. It is compatible with existing NTSC receivers, except that the display image is 16 : 9 aspect ratio and so appears in a letter-box format with black bars at top and bottom. The 525P signal requires a video bandwidth of approximately 6.2 MHz. The EDTV-II system creates three enhancement signals in addition to an NTSC signal, with which they are then frequency-domain-multiplexed.

Main Picture (MP). The 525P 16 : 9 signal is reduced from 6.2 MHz to 4.2 MHz bandwidth and the 480 lines are decimated to 360 lines to produce a letter-box display on the NTSC 4 : 3 receiver. Black bars, at top and bottom, are each 60 lines wide. Thus, horizontal and vertical resolution are reduced to conform to the NTSC format, but to maintain the 16 : 9 aspect ratio.

Horizontal High (HH 4.2 MHz to 6.2 MHz). A frequency enhancement signal is extracted from the original 525P image and is multiplexed into the MP signal to increase the horizontal bandwidth to 6.2 MHz in the EDTV-II receiver. For transmission, the HH signal is downshifted to 2 to 4 MHz and frequency-division-multiplexed into an unused vertical temporal frequency domain in the conventional NTSC system called the Fukinuki hole. The Fukinuki hole may only be used for correlated video information, which applies in this case.

In the EDTV-II receiver, a motion detector multiplexes the HH signal only onto the still parts of the picture where there is more need for high resolution to satisfy human vision characteristics. Two enhancement signals are frequency-division-multiplexed together into the top and bottom panels, which together occupy one-third as much area as the main picture. As these are generated in a 360 line format, they must be compressed by a 3 to 1 pixel downsampling decimation process to fit into the 120 lines of the top and bottom panels.

Vertical High Frequency (VH). The VH signal enhances the vertical still picture resolution back up to 480 lines. The signal is transmitted only for stationary areas of the image, and temporal averaging is applied.

Vertical Temporal Frequency (VT). The VT enhancement signal is derived from the progressive-to-interlace scan conversion at the encoder and improves the interlace-to-progressive scan (360/2 : 1 to 360/1 : 1) conversion in the receiver.

The EDTV-II receiver performs the reverse of the encoding process. The NTSC receiver uses the MP signal directly.

The European DVB System

The Digital Video Broadcast (DVB) system has been designed for MPEG-2-based digital delivery systems for satellite, cable, community cable, multichannel multipoint distribution (MMDS), and terrestrial broadcasting. Service information, conditional access, and teletext functions are also available. All DVB systems are compatible.

DVB-T, the terrestrial broadcasting standard, is similar in many respects to the ATSC standard. However, there are a number of significant differences. DVB-T uses Coded Orthogonal Frequency Division Multiplexing (COFDM). This technique is already being used for Direct Audio Broadcast (DAB). 1,704 (2k) or 6,816 (8k) individual carriers may be used. The 8k system is more robust, but increases receiver complexity and cost. Some broadcasters have already adopted the 2k system, although it will not be compatible with the 8k system. DVB-T uses the MPEG-2 Layer II Musicam audio standard, a 50 Hz frame rate, and aspect ratios of 4 : 3, 16 : 9, or 20 : 9.

The European PALplus System

This is an analog delivery system which uses a current TV channel to transmit an enhanced widescreen version of the

PAL signal. A conventional receiver displays the PALplus picture as a letter-box in a 4 : 3 aspect ratio. A widescreen receiver shows the same transmitted picture in a 16 : 9 format with higher resolution. European broadcasters are divided on whether to use this format. The PALplus concept is closely similar to the Japanese EDTV-II format, described above.

ACKNOWLEDGMENTS

The authors wish to sincerely thank the following for permission to use portions of their work in this article:

- The Advanced Television Systems Committee (ATSC) and its Executive Director, Craig Tanner, for text and figures from Standards A/52, A/53, and A/54.
- Mr. Stanley N. Baron, for text and figures from his book *Digital Image and Audio Communications, Toward a Global Information Infrastructure.*
- Mr. Patrick Griffis, for the data in a figure from his article Bits = Bucks, Panasonic, paper presented at NAB, 1998, unpublished.

BIBLIOGRAPHY

M. Ashibe and H. Honma, A wide-aspect NTSC compatible EDTV system, *J. SMPTE,* Mar. 1992, p. 130.

ATSC Digital Television Standard, Advanced Television Systems Committee, Doc. A/53, 16 Sept., 1995.

S. N. Baron (ed.), *Composite Digital Television: A Primer,* White Plains, NY: Soc. of Motion Picture and Television Eng., 1996.

S. N. Baron and M. I. Krivocheev, *Digital Image and Audio Communications, Toward a Global Information Infrastructure,* New York: Van Nostrand Reinhold, 1996.

K. B. Benson (ed.), *Television Engineering Handbook,* revised by J. Whitaker, New York: McGraw-Hill, 1992.

Digital Audio Compression Standard (AC-3), Advanced Television Systems Committee, Doc. A/52, 20 Dec., 1995.

A. Dubec, *The SECAM Colour Television System,* Paris: Compagnie Française de Télévision, 1976.

P. Griffis, Bits = Bucks, Panasonic, paper at NAB, 1998.

Guide to the Use of the ATSC Digital Television Standard, Advanced Television Systems Committee, Doc. A/54, 4 Oct., 1995.

A. Itoh, 525 line progressive scan signal digital interface standard and system, *J. SMPTE,* Nov. 1997, p. 768.

R. W. G. Hunt, *The Reproduction of Colour,* 5th ed., Kingston-upon-Thames: Fountain Press, 1995.

G. Hutson, P. Shepherd, and J. Brice, *Colour Television,* London: McGraw-Hill, 1990.

A. F. Inglis and A. C. Luther, *Video Engineering,* 2nd ed., New York: McGraw-Hill, 1996.

ISO/IEC IS 13818-1, International Standard MPEG-2 Systems, 1994.

ISO/IEC IS 13818-2, International Standard MPEG-2 Video, 1994.

ISO/IEC IS 13818-2, Section 8.

ITU-R BT.470-4, Characteristics of television systems, International Telecommunications Union, Geneva, 1995.

ITU-R Document, 11-3/15, MPEG digital compression systems, 9 Aug., 1994.

K. Jack, *Video Demystified,* 2nd ed., San Diego: HighText Interactive, 1996.

K. Jackson and B. Townsend (eds.), *TV & Video Engineer's Reference Book,* Oxford, England: Butterworth-Heinemann, 1991.

H. Y. Kim and S. Naimpally, Digital EDTV, compatible HDTV, *J. SMPTE,* Feb. 1993, p. 119.

B. Marti et al., Problems and perspectives of digital terrestrial TV in Europe, *J. SMPTE,* Aug. 1993, p. 703.

R. Mäusl, *Refresher Topics—Television Technology,* Munich: Rohde & Schwarz, 1992.

R. S. O'Brien (ed.), *Color Television, Selections from the Journal of the SMPTE,* New York: Society of Motion Picture and Television Engineers, 1970.

G. Pensinger (ed.), *4 : 2 : 2 Digital Video Background and Implementation,* White Plains, NY: Society of Motion Picture and Television Engineers, 1989.

D. H. Pritchard and J. J. Gibson, Worldwide color television standards—similarities and differences, *J. Soc. Motion Picture and Television Eng.,* **89**: 111–120, 1980.

Proc. IRE, Color Television Issue, **39** (10): 1951.

V. Reimer, Advanced TV systems, Germany and Central Europe, *J. SMPTE,* May 1993, p. 398.

M. Robin, Addendum to Worldwide color television standards—similarities and differences, *J. Soc. Motion Picture and Television Eng.,* **89**: 948–949, 1980.

M. Robin and M. Poulin, *Digital Television Fundamentals,* New York: McGraw-Hill, 1997.

T. Rzeszewski (ed.), *Color Television,* New York: IEEE Press, 1983.

T. S. Rzeszewski (ed.), *Television Technology Today,* New York: IEEE Press, 1984.

H. V. Sims, *Principles of PAL Colour Television and Related Systems,* London: Newnes Technical Books, 1969.

SMPTE 274M Standard for Television, 1920 × 1080 Scanning and Interface, 1995.

SMPTE S17.392 Proposed Standard for Television, 1280 × 720 Scanning and Interface, 1995.

V. Steinberg, *Video Standards, Signals, Formats, and Interfaces,* Durford Mill, England: Snell & Wilcox, 1997.

N. Suzuki et al., Matrix conversion VT resolution in letterbox, *J. SMPTE,* Feb. 1991, p. 104.

N. Suzuki et al., Experiments on proposed multiplexing scheme for vertical-temporal and vertical high helper signals in EDTV-II, *J. SMPTE,* Nov. 1994, p. 728.

Television Operating and Interface Standards, Society of Motion Picture and Television Engineers, 595 W. Hartsdale Ave., New York, NY 10607-1824.

Television Measurements Standards, Institute of Electrical and Electronic Engineers, Inc., Broadcast Technology Society, c/o IEEE Service Center, 445 Hoes Lane, Box 1331, Piscataway, NJ 08855.

J. Watkinson, *Television Fundamentals,* Oxford, England: Focal Press, 1996.

ALAN S. GODBER
JAMES R. REDFORD
IEEE BTS Audio–Video Techniques
Standards Committee

TELEVISION, DIGITAL. See DIGITAL TELEVISION.

TELEVISION, INTERACTIVE. See SET-TOP BOXES.

TELEVISION PICTURE TUBES. See CATHODE-RAY TUBES.

TEMPERATURE MEASUREMENT. See THERMOCOUPLES.