Chapter 1

Introduction to Analog and Digital Television

1.1. INTRODUCTION

From small beginnings less than 100 years ago, the television industry has grown to be a significant part of the lives of most people in the developed world, providing arguably the largest single source of information to its viewers.

The first true television system was demonstrated by John Logie Baird in the 1920s. Further experiments were conducted in the following decade, leading to trial broadcasts in Europe and the United States, and eventually to the regular television service we know today. Originally, only monochrome pictures were supported. Color television was introduced in the United States in 1954 and in Europe in 1967.

Television systems have evolved as *simplex* transmission systems, as shown in Figure 1.1. The term simplex means that information flows only in one direction across the channel. A transmitter, whose antenna is usually mounted on a tall tower, broadcasts a signal to a large number of receivers. Each receiver decodes the transmission and passes it on to a display device. Sometimes, the receiver and display are integrated into a single device, such as in a standard television that incorporates a means for the user to select the channel to be viewed. Sometimes, the receiver and display are separate devices, such as when a signal is received through a video cassette recorder (VCR) and passed to an external display. This system is known as *terrestrial broadcast* television.

Satellite and cable television systems operate on similar models. Figure 1.2 shows the outline structure of a cable television system.

1.2. ANALOG TELEVISION

Traditional television services make use of analog technology to provide an audiovisual, broadcast service. The basic structure of an analog television transmitter is shown in Figure 1.3. Video and audio signals, which may be derived from live sources such as cameras and microphones or from storage devices such as video

Digital Television, by John Arnold, Michael Frater and Mark Pickering.

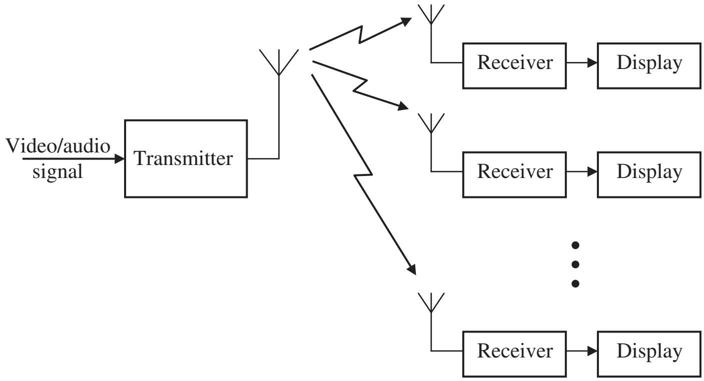

Figure 1.1 Simplex structure of terrestrial broadcast television.

recorders, are fed into separate modulators, whose output is multiplexed and upconverted to form the broadcast signal.

Various methods of modulating, multiplexing, and upconverting the signals to specific broadcast frequencies (as shown in Figure 1.3) are defined in the various analog television standards. Three of the major standards used for analog television are National Television System Committee (NTSC) [1], used primarily in North, Central, and South America, Systeme Electronique (pour) Couleur avec Memoire (SECAM), used in France and countries in eastern Europe such as Poland and Russia, and Phase Alternating Line (PAL) [2], used in many other countries including western Europe and Australia.

In this chapter, we discuss the operation of analog television with reference to three areas: the representation of video, the representation of audio, and the systems that provide the multiplexing of video and audio services into a single channel.

1.2.1. Video

An analog video signal is created by a time sequence of pictures, with 25 or 30 of these pictures displayed every second. Each picture consists of a number of lines,

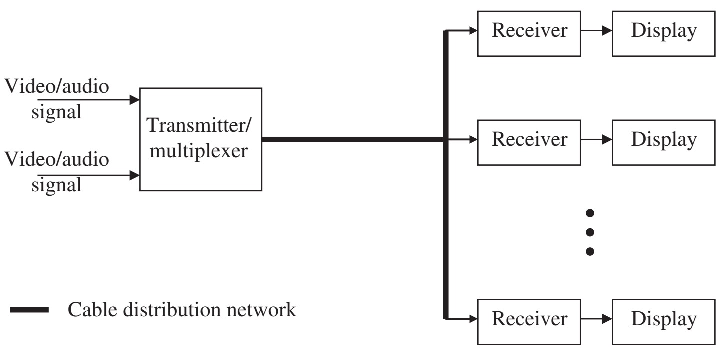

Figure 1.2 Structure of a cable television system.

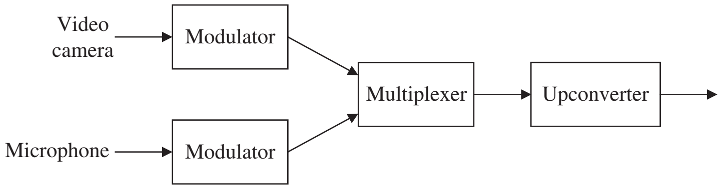

Figure 1.3 Basic structure of an analog television system.

each of which is scanned left to right, as illustrated in Figure 1.4. The vertical resolution is usually 576 lines for 25 Hz systems and 480 lines for 30 Hz systems.

In addition to the displayed lines, a number of other lines of data are transmitted. These are intended to provide time for the scan in a cathode ray tube to return from the bottom right of the display at the end of one picture to the top left of the display at the beginning of the next picture. The inclusion of these nondisplayed lines brings the total number of lines per picture to 625 for 25 Hz systems and 525 for 30 Hz systems. The time in which these nondisplayed lines are transmitted is known as the *vertical blanking interval* (*VBI*).

1.2.1.1. Horizontal Synchronization

In an analog television signal, a synchronization pulse is provided at the start of every line in the picture as shown in Figure 1.5, which shows the waveform for a single line where the brightness decreases in steps from left to right. This means that the display begins its horizontal scan at the same place in the signal as the camera that captured the video signal. In addition, a longer synchronization pulse is used to indicate that the scan should restart at the top left of the display. These synchronization pulses allow the receiver to achieve synchronism with the incoming signal.

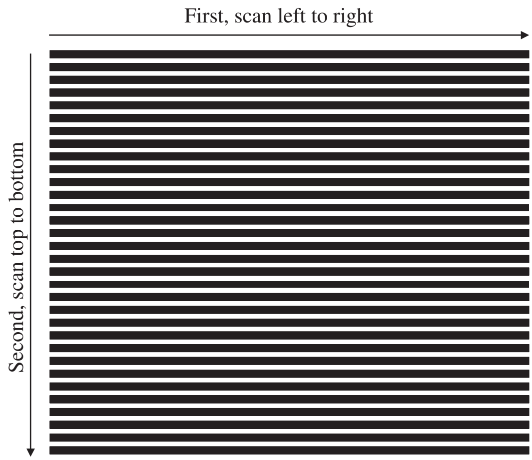

Figure 1.4 Simple left-to-right, top-to-bottom scan.

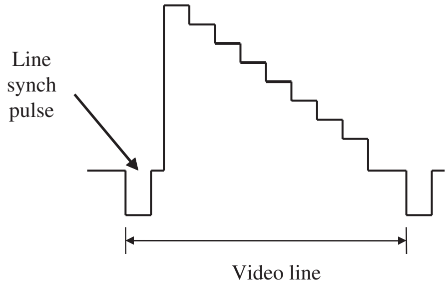

Figure 1.5 Waveform of a single picture line of analog video.

The interval allocated for transmission of the line synchronization pulse and the immediately surrounding regions (known as the front and back porches) is known as the *line blanking interval* or the *horizontal blanking interval*. Its length is 11 μs in NTSC and 12 μs in PAL and SECAM systems.

1.2.1.2. Horizontal Resolution

The horizontal resolution of an analog television system depends on the bandwidth of the video signal. Roughly speaking, the resolution of the system is 2 pixels per Hertz of video bandwidth. These pixels are shared equally between the transmitted lines. The number of useful pixels in each line is reduced by the length of the line blanking interval. The horizontal resolution r_h of an analog video system with bandwidth B is therefore

$$r_h = 2Bt_{ULI}$$

where t_{ULI} is the useful line interval. The horizontal resolutions for a number of in-service analog television systems are shown in Table 1.1. In the case of PAL and SECAM, there are a number of different implementations, each denoted by a

Table 1.1 Approximate horizontal resolution for selected analog television systems.

System	Lines per second (KHz)	Line period (μs)	Useful line interval (line period – line blanking interval) (μs)	Video bandwidth (B) (MHz)	Approximate horizontal resolution (pixels)
NTSC	15.750	63.5	52.5	4.2	441
PAL (B, G, H)/ SECAM (B, G)	15.625	64.0	52	5.0	520
PAL (I)	15.625	64.0	52	5.5	572
PAL (D)/SECAM (D, K, K1, L)	15.625	64.0	52	6.0	624

single letter. The video bandwidth varies between implementations, and a number of options are shown.

1.2.1.3. Interlaced Video

When analog television was designed, an important design trade-off was between the service picture rate and the service bandwidth. The picture rate chosen needs to be sufficiently fast to ensure that a human viewer perceives an apparently continuous service (as opposed to a rapid series of individual pictures—called flicker—which would be subjectively most unpleasant). Once the appropriate horizontal and vertical resolution of a television picture had been decided, the desired bandwidth meant that a relatively low picture rate (25 or 30 Hz) was all that could be achieved. These picture rates are insufficient to avoid flicker in all circumstances. However, simply increasing the picture rate would lead to an increase in the required service bandwidth. This was an unacceptable outcome. The developers of analog television overcame this problem using a technique called interlacing.

Interlacing divides each picture into two fields, as shown in Figure 1.6. One field contains the odd lines from the picture (i.e., lines 1, 3, 5, …) and is called the odd field, whereas the other field contains the even lines from the picture (i.e., lines 2, 4, 6,…) and is called the even field (Figure 6(a)). The odd lines are scanned from the camera system and then half a picture time later (i.e., 1/50th or 1/60th of a second) the even lines are scanned (Figure 6(b)). This approach improves the rendition of moving objects and also completely removes the flicker problem discussed earlier. The trade-off is some loss in vertical resolution of the picture.

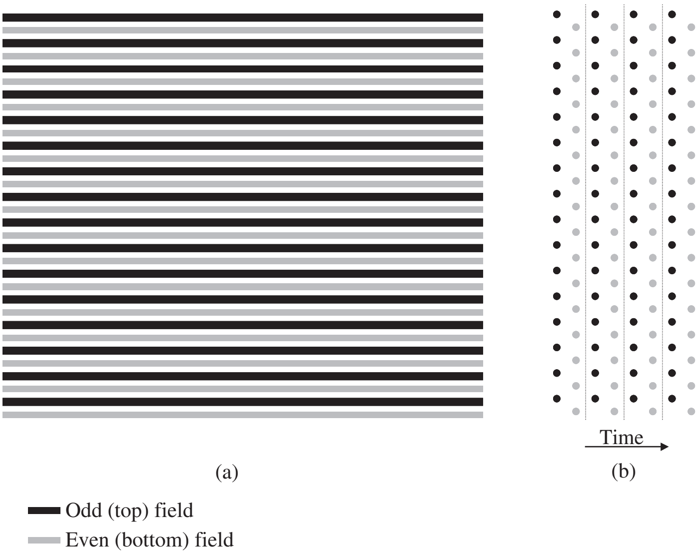

Figure 1.6 Interlace structure showing location of odd and even fields, (a) as seen on the display, and (b) the formation of pictures from two consecutive fields.

Table 1.2 Numbers of video lines per field and picture.

System	Notional picture frequency Hz	Field frequency Hz	Displayed lines per picture	Displayed lines per field	Total lines per picture	Total lines per field
PAL, SECAM	25	50	576	288	625	313 (odd)/ 312 (even)
NTSC	30	60	480	240	525	263 (odd)/ 262 (even)

Table 1.2 shows the number of lines per picture and field for 25 and 30 Hz analog television systems.

EXAMPLE 1.1—MATLAB

The aim of this example is to demonstrate the impact of combining two fields containing a moving object into a single picture.

SOLUTION Figure 1.7 shows two fields of 128 × 128 pixels consisting of a black background and a white square of size 32 × 32 pixels that has moved four pixels to the right between fields.

```
A = zeros(128);                    % black background for odd field
B = zeros(128);                    % black background for even field
A(49:80, 49:80) = 255 × ones(32);    % white square in odd field
B(49:80, 57:88) = 255 × ones(32);    % white square in even field
(moved 8 pixels right)
```

The individual fields can be displayed using the MATLAB function image.m:

```
image(A)                    % display odd field
image(B)                    % display even field
```

The images obtained by displaying *A* and *B* are shown in Figure 1.7.

The two fields can be merged into a single picture, which is then displayed, using the commands below.

```
C = zeros(256,128);
C(1:2:255,:) = A;
C(2:2:256,:) = B;
image(C);
```

Figure 1.7 Odd and even fields produced in Example 1.

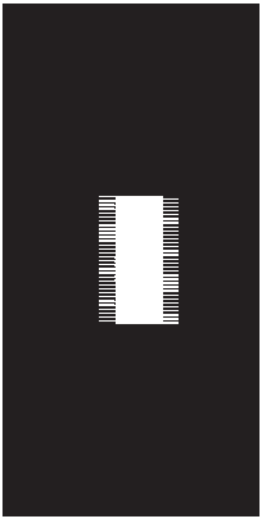

Figure 1.8 Merged fields to form a picture.

The resulting image is shown in Figure 1.8. The jagged edges are caused by the movement of the white block between the odd and even fields. In some circumstances, these jagged edges can lead to localized flickering. ■

When fields containing moving objects are merged to form a single picture, straight edges that are moving horizontally are turned into jagged edges. An example from the "Mobile and Calendar" sequence is shown in Figure 1.9, in which the jagged edges of moving objects such as the spots on the ball and the numbers on the calendar are clearly apparent.

1.2.1.4. Color Television

Television was initially a monochrome (black-and-white) service. When color television was to be introduced, the color information needed to be introduced in a way that did not affect substantially the quality of service received by consumers who still had a black-and-white television receiver. As is well known, color receivers display only three colors (red (R), green (G), and blue (B)). The mixing of these colors at the human eye provides the range of colors that we are used to with color television.

Transmitting separate signals for red, green, and blue would triple the bandwidth requirement for color television compared to monochrome television. Because a monochrome signal is not present in this set, the only way to provide a good quality monochrome picture for existing receivers would be to send yet another signal just for this purpose; this would be a very wasteful use of valuable spectrum. The quality of reception at monochrome receivers would have been significantly compromised.

Figure 1.9 Picture from the "Mobile and Calendar" sequence.

The approach taken was to transmit not the color signals *R*, *G*, and *B* but the monochrome signal (known as the luminance *Y*) accompanied by two color difference, or chrominance, signals (*U* and *V*) from which the three colors *R*, *G*, and *B* can be reconstructed. The values of the luminance signal and two chrominance signals can be calculated from *R*, *G*, and *B* according to

$$Y = 0.299R + 0.587G + 0.114B$$
$$U = \frac{B - Y}{2.03}$$
$$V = \frac{R - Y}{1.14}$$

Slightly different versions of these equations are used in different television systems.

The three color signals *R*, *G*, and *B* are reconstructed at the receiver and displayed. Because the luminance signal is still transmitted, it is still available to monochrome receivers and so there is a minimal impact on existing viewers. The color difference signals can also be transmitted with a significantly smaller bandwidth than the luminance signal. This is acceptable because the resolution of the human eye is lower for chrominance than it is for luminance. The use of color difference signals was therefore an early attempt at bandwidth compression.

1.2.2. Audio

The audio accompanying video in an analog television system usually has a bandwidth of approximately 15 kHz. The audio system in analog television originally supported only a single (monophonic) channel. It has been extended with the same philosophy of backward compatibility used for adding color information in the video to provide a range of services, including options for stereo audio, and two independent audio channels. In all cases, the original monophonic audio is still transmitted to support older receivers, with other signals added to provide higher levels of functionality.

1.2.3. Systems

Specification of the representation of audio and video is not sufficient to define a television service. A means is required to multiplex the video signals (luminance and chrominance) and the audio (mono or stereo) onto a single channel. We refer to this capability as the “systems” part of the television service.

Each country specifies a channel bandwidth for broadcast television systems. In North and Central America, 6 MHz is used, whereas 7 or 8 MHz is commonly used in the rest of the world. Approximately 70% of the bandwidth of the channel is allocated to video, with the remaining capacity available for audio and guard bands between channels.

Figure 1.10 shows the spectrum of a typical, monochrome, analog television channel with a single audio channel. Most of the capacity of the channel is allocated to the video, with a small amount available for audio. The video signal is usually modulated using vestigial sideband amplitude modulation with the upper sideband dominant, whereas the audio signal is frequency modulated with a maximum deviation of approximately 50 kHz (giving an audio bandwidth of 100 kHz). The audio carrier is located within the channel, but outside that part of the channel specified for the transmission of video. Each of the analog television standards specifies the locations of the video and audio carriers.

Extension to support color television can be achieved by the multiplexing of the chrominance signals onto the channel, as shown in Figure 1.11. This is done by using

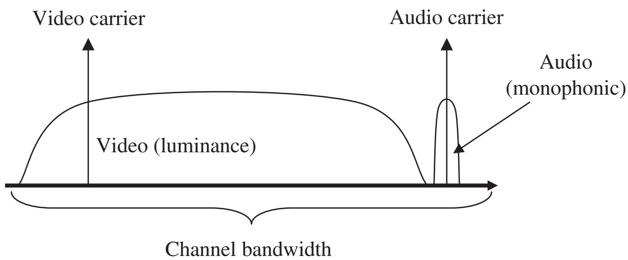

Figure 1.10 Spectrum of a typical monochrome analog television channel.

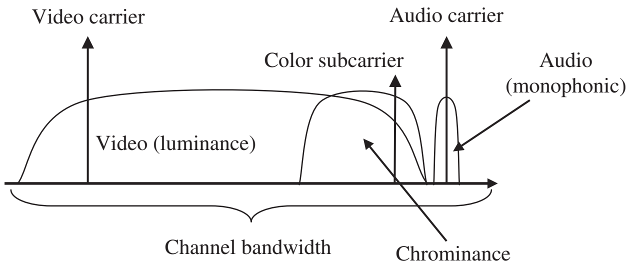

Figure 1.11 Spectrum of a color analog television channel.

vestigial sideband modulation for the chrominance signal, with the lower sideband dominant. Each of the three standards specifies the location for the color subcarrier, which is the carrier frequency associated with the modulation of the chrominance signal. The carriers for the two chrominance signals have the same frequency, but differ in phase by 90°. This "phase multiplexing" allows separation of the signals at the receiver. Noting that most of the energy in video signals occurs at low frequencies, the chrominance information is transmitted toward the upper end of the video spectrum. This does have the effect that high-frequency luminance information can sometimes be mistakenly decoded as color information. It is for this reason that herringbone tweed jackets sometime flair purple on color television receivers. The high-frequency monochrome information from the tweed is incorrectly decoded as color information. The problem has been addressed by television producers becoming aware of the problem and making sure that presenters do not wear inappropriate clothing.

A second audio channel can be incorporated simply by specifying the location of its carrier. Frequency modulation is usually also used for the second audio channel. Backward compatibility is maintained by ensuring that a valid monophonic audio signal for the program is transmitted on the original audio carrier. This is illustrated in Figure 1.12.

Each of the various standards for analog television (NTSC, PAL, and SECAM) specifies frequencies for the video carrier, color subcarrier, and audio carriers. Each standard also specifies maximum bandwidths for the video and each of the audio channels.

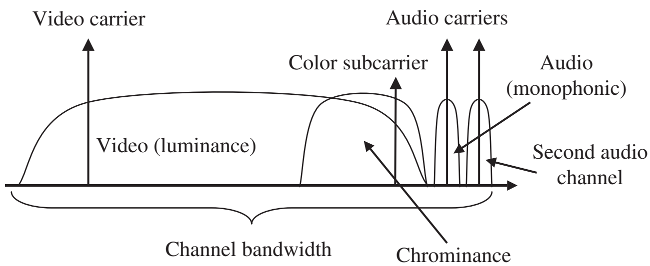

Figure 1.12 Spectrum of a typical color analog television channel with stereo audio.

1.2.3.1. Ancillary Services

Analog television systems have evolved to carry not only audio and video signals, but also a range of ancillary data services. These ancillary services make use of the nondisplayed lines of the video vertical blanking interval to provide low-rate data services such as closed captioning (also known as subtitling) and teletext. Because these services are carried in the vertical blanking interval, they have no impact on receivers that are not equipped to decode them.

1.3. THE MOTIVATION FOR DIGITAL TELEVISION

The initial impetus for moving to a digital signal was standards conversion (e.g., from 525 line NTSC at 30 pictures/s to 625 line PAL at 25 pictures/s). This is an extremely difficult process in the analog domain. Significant signal processing is still required in the digital domain. However, appropriate high-speed hardware can be built to allow the task to be successfully carried out. Other motivations for the change from analog to digital television include carrying multiple digital television channels within the existing bandwidth allocated to a single analog television service, the ability to carry higher resolution services (such as high-definition television) in a single channel, and the integration of a range of interactive services into the television broadcast.

From a communication point of view, digital transmission has many advantages. In particular, it offers considerable noise immunity. Consider the analog signal shown in Figure 1.13. The original analog signal is perturbed by noise. If the noise is

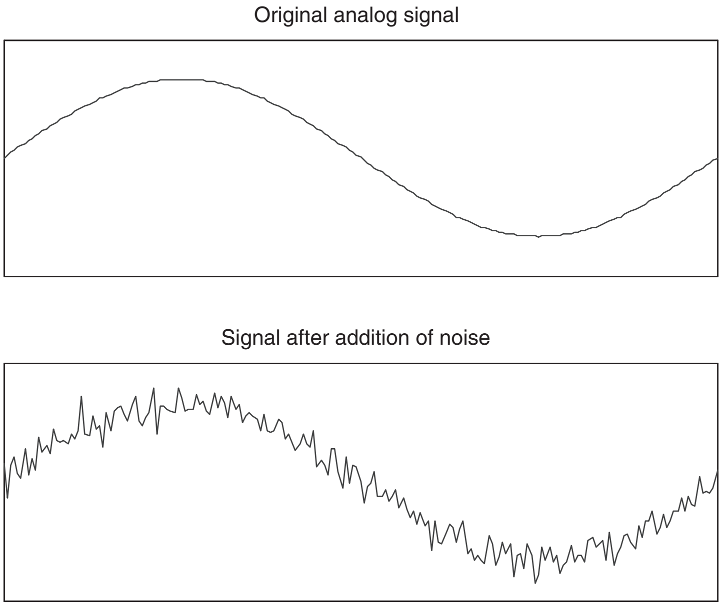

Figure 1.13 Impact of noise on an analog signal.

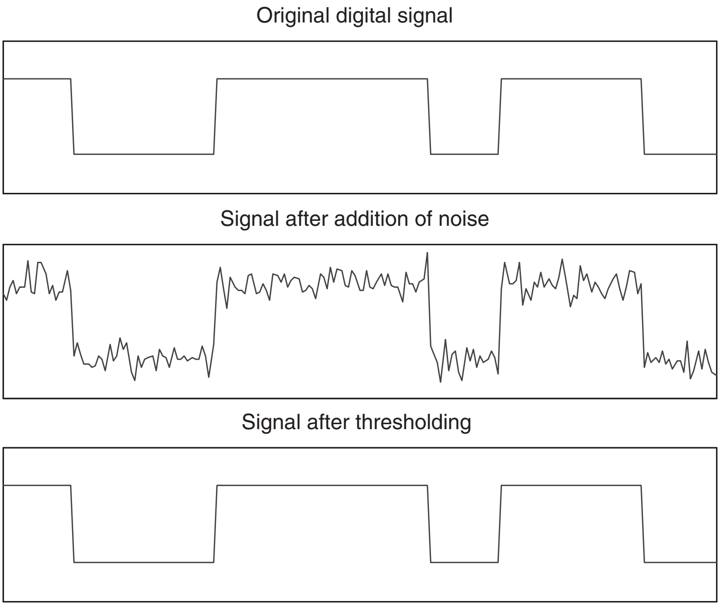

Figure 1.14 Impact of noise on a digital signal.

in the same area of the spectrum as the signal (so-called in-band noise), then there is little that can de done to remove it.

The impact of noise on a digital signal is quite different, as illustrated in Figure 1.14. In this case, a simple thresholding operation allows the original signal to be perfectly reconstructed. Even when the noise is large enough to cross the threshold, enhanced signal processing techniques such as matched filtering [3] can be employed to achieve good performance (which can be improved still further using error correction techniques such as those described in a later chapter). The ability of digital signals to reject noise makes digital systems ideal for long-distance transmission because quality can be maintained through many repeaters.

Other advantages of digital systems include the fact that digital components are of low cost and are very stable. In addition, many digital networks are now emerging for the transmission of audiovisual material at a range of transmission rates.

1.4. THE NEED FOR COMPRESSION

If digital systems offer so many advantages, why have we not moved to digital television long ago? The answer lies in the very high data rates required for transmitting raw, uncompressed digital video and the complexity of the digital systems required to provide real-time processing for compression and decompression.

Table 1.3 Resolution of digital television.

Picture rate (Hz)	25	30
Lines per picture	576	480
Luminance samples per line	720	720
Fields per second	50	60
Interlace	Two fields per picture (2:1)	Two fields per picture (2:1)

The resolution defined for digital television by the ITU-R Recommendation BT.601 [4] is given in Table 1.3. The number of lines per picture is the same as the number of displayed lines for the analog services. When an analog television signal is converted to digital, the nondisplayed lines in the vertical blanking interval are removed. For both 25 and 30 Hz transmission, 14,400 lines per second are transmitted, which means that 10,368,000 pixels (or luminance samples) must be transmitted each second.

For distribution of digital television, each chrominance signal is sampled at half the rate of the luminance signal, that is, at 360 samples per line. Thus, there is one sample of each of the chrominance components (U and V) for every two luminance components (Y). If each of the Y, U, and V is represented to 8-bit accuracy, then an average of 16 bits is required for each luminance sample.

The raw bit rate is therefore 10,368,000 luminance samples per second multiplied by 16 bits per sample, giving a data rate of 165.89 Mbit/s. Even in the highest capacity, modern, communications networks, this is an extremely high capacity to be allocated to a single service.

The corresponding bandwidth requirement for various digital modulation schemes is shown in Table 1.4, each of which is much greater than the 6, 7, or 8 MHz allocated for the transmission of an analog television service. If digital television is to compete effectively with analog television, it needs to be able to utilize a bandwidth not more than (and preferably significantly less than) an equivalent analog service. Of course, the raw data rate could be reduced to achieve this

Table 1.4 Bandwidth requirement for uncompressed digital video using various digital modulation schemes.

Modulation scheme	Bits/second/Hertz of bandwidth	Required bandwidth (MHz)
Binary phase-shift keying (BPSK)	1	165.89
Quadrature phase-shift keying (QPSK)	2	82.94
8-ary phase-shift keying (8-ary PSK)	3	55.30
256-ary quadrature amplitude modulation (256-ary QAM)	8	20.74

goal. This could be done by reducing either the number of samples per line, the number of lines per picture, or the number of pictures per second. Such an approach would seriously affect the quality of the received service and so is not a viable solution.

A similar method can be used to calculate the rate required for transmitting uncompressed digital audio. If each channel of audio is sampled at 44.1 kHz with a resolution of 16 bits per sample, 705.6 kbit/s is required per channel. For five-channel audio (such as that used for surround-sound systems), a total of 3.5 Mbit/s is required. Although this is much less than the rate required for raw digital video, it still represents a significant expansion of the bandwidth requirement for the audio service compared to analog television.

Fortunately, the characteristics of the video and audio signals are such that significant savings are possible in the amount of data that needs to be transmitted in order to adequately represent the original signals. The digital signal processing techniques that allow this aim to be achieved will be a major focus of the first two parts of this text. It turns out that 5–10 Mbit/s is a reasonable target bit rate for a digital television service, with approximately 10% of the available data rate taken by transmission overheads, 10% allocated to audio, and the remaining 80% to video. Under these circumstances, compression factors of approximately 40 are required for digital video (meaning that the compressed digital video should require one fortieth of the rate required by the uncompressed video) and 10 for digital audio.

1.5. STANDARDS FOR DIGITAL TELEVISION

The use of standards in television broadcast systems is critical to their success. It is necessary that a consumer be able to purchase a receiver from any manufacturer and be confident of being able to watch television transmissions from any television broadcaster. Standards have always played a major part in providing this interoperability. For analog television, these were NTSC, PAL, and SECAM.

Modern digital television systems are based on one of the two standards, both named after the groups that developed them. The US *Advanced Television Systems Committee* (*ATSC*) [5] family of standards is used in North America, whereas the *Digital Video Broadcast* (*DVB*) [6] family of standards is used in much of the rest of the world, including Europe, much of Asia, and Australia.

DVB uses the MPEG-2 video standard [7] to provide video compression, the MPEG-2 audio standard [8] for audio compression, and the MPEG-2 systems standard [9] to multiplex the compressed video and audio with other data for transmission. Additional DVB standards extend the functionality of the MPEG-2 systems specification and specify how additional data (including subtitling and teletext) are carried in the bit stream.

ATSC also uses the MPEG-2 standards for video compression and multiplexing. Instead of using the MPEG-2 audio standard, ATSC specifies its own standard for

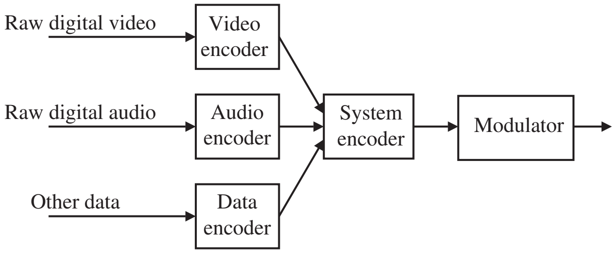

Figure 1.15 Outline structure of a digital television encoding and transmission system.

audio compression, which uses the Dolby AC-3 compression system [10]. Like DVB, ATSC specifies additional standards for carrying data (including closed captioning) in the bit stream.

The DVB and ATSC standards are available free of charge, at the time of writing. MPEG standards are available for purchase through national bodies affiliated to the International Standards Organization. In all cases, sufficient information is provided in this text for the reader to understand how the technology embedded in each relevant standard works. Access to the standard would be required, however, for a complete implementation to be developed.

The notional structure of a digital video transmitter is shown in Figure 1.15, consisting of separate encoders for each type of signal to be included in the transmitted program, a system encoder that multiplexes the outputs of these encoders and a modulator that converts the multiplexed bit stream into a form suitable for transmission in the same channel as that used for analog television. Part 1 of this book is concerned with the characteristics of the video encoder, its output bit stream, and the corresponding decoder. Part 2 is concerned with the audio encoder, its output bit stream, and decoder. Part 3 of the book covers the system encoder, encoders for other types of data, and modulation.

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