CHAPTER

19 Television systems

Television system dissect the image and transmit the pixel information serially. The image is divided into a stack of horizontal stripes ("lines") which are scanned left to right, producing a sequence of pixel (picture element) brightness values. The lines are scanned in order, one after the other, from top to bottom. Brightness values for each pixel are transmitted to the receiver(s). The image is reconstructed by a display device, whose pixels are illuminated according to the received brightness values. This chapter presents television technology in historical order: (1) the electromechanical system that Nipkov patented in 1884 but which was not demonstrated until 1923; (2) all-electronic television, made possible by the development of cathode ray picture tubes and camera tubes; and (3) digital television, which uses data storage and processing in the receiver, allowing the station to update the changing parts of the image, rather than retransmit the entire image for every frame. With the lowered data rate, the bandwidth needed previously to transmit one analog television program can now hold multiple programs.

19.1 The Nipkov system

Electronic image dissection and reconstruction were first proposed in the Nipkov disk system, patented in 1884, which used a pair of rotating disks, as shown in Figure 19.1. The camera disk dissected the image while the receiver disk reconstructed it. The receiver screen, a rectangular aperture mask, was covered by an opaque curtain containing a pin hole, illuminated from behind by an intensity-modulated gas discharge lamp. The position of the pin hole was analogous to the position of the illuminated spot on a CRT. This scanning pinhole was actually a set of *N* pinholes, arranged in a spiral on an opaque disk that rotated behind the aperture mask. Only one hole at a time was uncovered by the aperture. As the active hole rotated off the right-hand side of the aperture, the next hole arrived at the left-hand side, displaced downward by one scanning line. Identical holes in the transmitter disk

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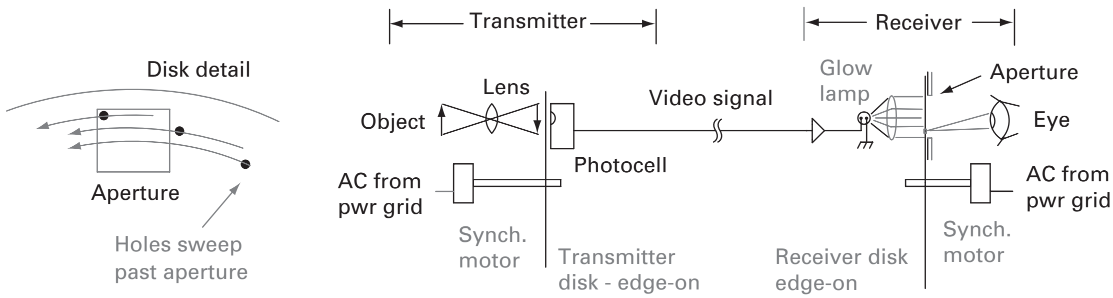

Figure 19.1. Nipkov rotating disk television system.

allowed light from the original image to hit a photocell. Of course the rotating disks had to be synchronized, but when the disks were driven by synchronous motors on the same ac power grid, it was only necessary to find the correct phase.

This primitive low-resolution system was finally demonstrated in 1923 after the invention of the photoelectric cell, vacuum tube amplifier, and neon glow lamp. While the eye views only a single illuminated spot, the persistence of human vision retains an image on the retina of the eye long enough to make the image appear complete if the entire screen is scanned at a rate more than about 20 times per second.[1] Some early experimental broadcasts were made with this very low resolution system in the U.S. on 100-kHz wide channels in the 2–3 MHz range.

19.2 The NTSC system

All-electronic television broadcasts were first made in Germany in 1935 and in England in 1936. The system used in the United States was proposed by the National Television Standards Committee (NTSC) of the Radio Manufacturers Association (RMA). Commercial broadcasting using the NTSC began on July 1, 1941. NBC and CBS both started television service that day in New York City. These stations and four others (Philadelphia, Schenectady, Los Angeles, Chicago) maintained broadcasts throughout World War II to some 10–20 thousand installed receivers. Compatible color broadcasting was added to the NTSC standard in the early 1950s. An engineering tour de force, this system effectively transmits simultaneous red, green, and blue images through the original 6-MHz channels in such a way that monochrome receivers are unaffected.

The NTSC standard specifies a horizontal-to-vertical aspect ratio of four-to-three for the raster (German for screen) with 525 horizontal lines, each scanned in 62.5 microseconds. About 40 of these lines occur during the vertical retrace interval, so there are some 525−40 or 485 lines in the picture. If the horizontal

[1] The florescent “phosphorous” material on a television CRT faceplate provides addition persistence.

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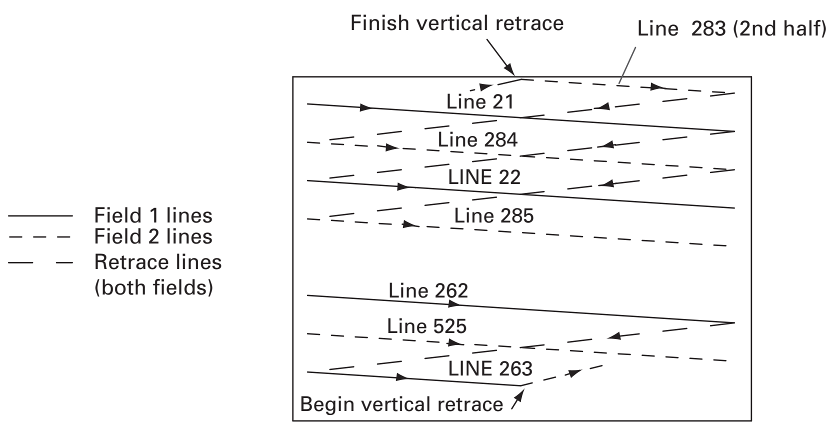
resolution were equal to the vertical resolution, the number of horizontal picture elements would be $4/3 \times 485 = 646$. The NTSC standard specifies somewhat less horizontal resolution: 440 picture elements. The horizontal retrace of a CRT requires about ten microseconds, so the active portion of each line is $62.5 - 10 = 52.5$ microseconds. The maximum video frequency is therefore given by $\frac{1}{2} \times 440/52.5 = 4.2$ MHz. (A video sine wave at 4.2 MHz would produce 220 white stripes and 220 black stripes.)

19.2.1 Interlace

The NTSC frame rate is 30 Hz, i.e., the entire image is scanned 30 times each second. The line rate is therefore $525 \times 30 = 15\,750$ Hz. Interlaced scanning is specified. This is shown in Figure 19.2. Lines 1–262 and the first half of line 263 make up the first field. The second half of line 263 plus lines 264–525 make up the second field. The lines in the second field fit between the lines of the first field. Each field takes 1/60 sec, fast enough that the viewer perceives no flicker. If all 525 lines were scanned in 1/60 sec, the signal would require twice the bandwidth and the CRT beam deflection circuitry would require more power. Interlacing provides full resolution for fixed scenes but creates artifacts on moving objects (see Problem 19.5).

Figure 19.2. Interlaced scanning.



19.2.2 The video signal

The video signal amplitude-modulates the video transmitter. Synchronization pulses are inserted between every line of picture information. The NTSC system uses negative video modulation so that less amplitude denotes more brightness. The principal reason for using this polarity is that impulse interference creates black dots rather than more visible white dots on the screen of the receiver.

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19.2.3 Synchronization

A horizontal sync pulse is inserted in the retrace interval between each scanning line and is distinguished by having a higher amplitude than the highest amplitude picture information, i.e., the sync pulse is “blacker” than the black level already blanking the beam during the retrace. The composite video, picture information plus synchronizing pulses, is shown in Figure 19.3. This waveform, which would be observed at the output of the video detector after lowpass filtering to remove the 4.5 MHz sound, shows three successive scan lines.

Television receivers have a threshold detector in the synchronization circuitry in order to look only at the tips of the sync pulses, i.e., the portion that is above the black level, and therefore totally independent of the video information. The burst of eight sinusoidal cycles at 3.579 545 MHz on the “back porch” of each synch pulse provides a reference for the color demodulator, described later. A vertical sync reference is provided by a series of wider sync pulses that occur near the beginning of the vertical blanking period, i.e., every 1/60 second at the end of every field.

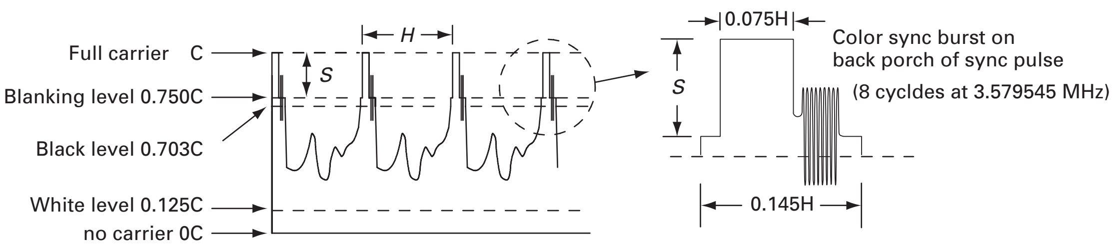

Figure 19.3. NTSC video waveforms.

19.2.4 Modulation

Radio transmission of video information (television) requires that we modulate a carrier wave with the composite video signal. The NTSC system uses full-carrier AM modulation for the video. Since the NTSC video signal extends to 4.2 MHz, ordinary double-sideband AM would require a bandwidth of 8.4 MHz. To save bandwidth, the lower part of the lower sideband is removed at the transmitter by filtering, allowing a 6-MHz channel spacing. The resulting *vestigial sideband* signal consists of the entire upper sideband, the carrier, and a vestige of the lower sideband, as shown in Figure 19.4.

At the receiver, a low-frequency video component, because it is present in both sidebands, would produce twice the voltage that would be produced by a high-frequency video signal, present only in the upper sideband. This problem is corrected by using an IF bandpass shape that slopes off at the lower end such as shown in Figure 19.5. At the video carrier frequency the amplitude response is ½. (This response is as good as and simpler to obtain than the dotted curve where all of the double sideband region is reduced to ½.)

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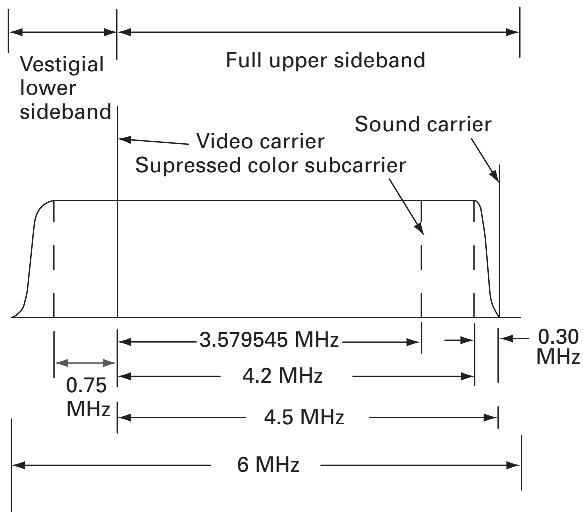

Figure 19.4. NTSC 6-MHz channel allocation.

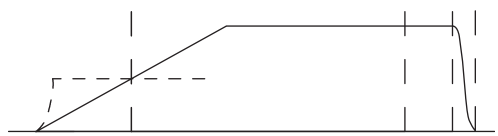

Figure 19.5. IF response to equalize the vestigial sideband.

For this IF equalization to work correctly, this IF filter should also have linear phase response. When surface acoustic wave (SAW) filters became available to determine the IF bandpass shape, this requirement was easily satisfied.

19.2.5 Sound

The audio or "aural" signal is transmitted on a separate carrier, 4.5 MHz higher in frequency than the video carrier. The NTSC system uses FM modulation for the audio component. The maximum deviation is 25 kHz, i.e., the maximum audio amplitude shifts the audio carrier 25 kHz. Normally the audio transmitter is separate from the visual transmitter and their signals are combined with a diplexer to feed a common antenna.

19.2.6 NTSC color

The NTSC standard for compatible color television was adopted in 1953. Like color photography, color television is based on a tricolor system. When two or more colors land at the same spot on the retina, their relative intensities determine the perceived hue. When three complete images in three suitably chosen primary colors are superimposed, the eye perceives a full-color image. The particular red, green, and blue standards specified in the NTSC standard

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were based on practical phosphors used for the dots on the faceplate of the CRT. Since color television requires the simultaneous transmission of three images, it is interesting to see how the color system can shoehorn three images into the 6-MHz channel originally allocated for a single monochrome image and do it in a way that made color broadcasts compatible with existing monochrome receivers. The solution to the bandwidth problem takes advantage of the fact that the monochrome video signal leaves empty gaps across the 6-MHz band. There is considerable redundancy in a typical picture. In particular, any given line is usually very much like the line preceding it (producing strong correlation at 62.5 microseconds) so the video signal is similar to a repetitive waveform with a frequency of 15 750 Hz, the horizontal scan frequency. If the lines were truly identical, the spectrum would be a comb of delta functions at 15 750 Hz and its harmonics. Since one line differs somewhat from the next, these delta functions are broadened, but the spectral energy is still clumped around the harmonics of the horizontal scanning frequency, leaving relatively empty windows which can be used to transmit color information. (Note that if the entire picture is stationary then the spectrum is a comb of delta functions spaced every 30 Hz and essentially all the bandwidth is unused.)

Instead of transmitting the red, blue, and green (RGB) signals on an equal basis, three linear combinations are used. One of these, the *luminance* signal, Y, is chosen to be the brightness signal that would have been produced by a monochrome camera: $Y=0.299R+0.587G+0.114B$. The other two linear combinations are $I=0.74(R-Y)-0.27(B-Y)$ and $Q=0.48(R-Y)+0.41(B-Y)$.

The luminance signal directly modulates the carrier, just as in monochrome television, and monochrome receivers respond to it in the standard fashion. Each of the other two signals, I and Q, modulates a subcarrier (just as the Right-minus-Left audio signal modulates a 38-kHz subcarrier in FM stereo). The color subcarriers have the same frequency, 3.579 545 MHz, but they differ in phase by 90°. Figure 19.6 shows how two independent signals are transmitted and recovered using this quadrature AM modulation (QAM).

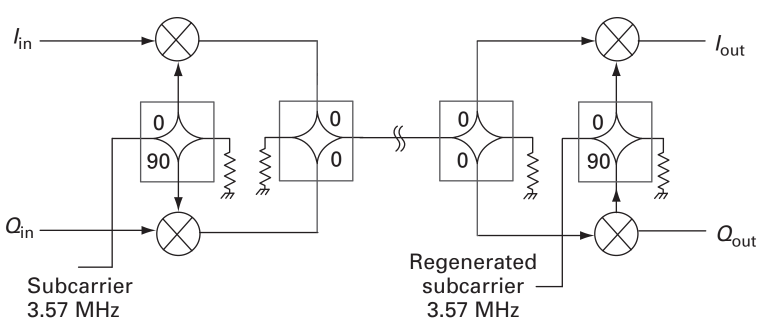

Figure 19.6. Quadrature AM modulator/demodulator lets the two color signals occupy one band.

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The reference signal necessary to regenerate these local carriers is sent as a burst of about eight sinusoidal cycles at 3.579 545 MHz on the back porch of each horizontal sync pulse as shown in a previous figure. This "color burst" is used in the receiver as the reference for a phase lock loop. The color information, like the luminance information, is similar from line to line so its power spectrum is also a comb whose components have a spacing equal to the horizontal scanning frequency. The subcarrier frequency is chosen at the middle of one of the spectral slots left by the luminance signal so the comb of color sidebands interleaves with the comb of luminance sidebands – a frequency multiplexing technique known as spectral interlacing.

Compatibility is achieved because the spectral interlacing greatly reduces visible cross-talk between chrominance and luminance information. To see this, consider a very simple signal, a uniform color field such as an all-yellow screen. Since this field has a color, i.e., it is not black, white, or gray, there will be nonzero I and Q signals. In this example, since the color information is constant, the I and Q signals together are just a sine wave at the color subcarrier frequency. Their relative amplitudes determine the hue while their absolute amplitudes determine the saturation. One would expect this 3.58-MHz video component to produce vertical stripes. And the beam, as it sweeps across the screen, does indeed get brighter and dimmer at a 3.58-MHz rate, trying to make some 186 stripes in the 52.5 microsecond scan. But, on the next line, these stripes are displaced by exactly one half-cycle. The result is that the entire screen, rather than having 186 vertical stripes, has a fine-gridded checkerboard or "low visibility" pattern. Colored objects viewed on a monochrome receiver can be seen to have this low visibility checkerboard pattern. Note that there are some unusual situations where spectral interleaving does not work. If the image itself is like a checkerboard with just the right grid spacing the luminance signal will fall into the spectral slots allocated for the chrominance signal and vice versa. A herringbone suit for example, will often have a gaudy sparkling appearance when viewed on a color receiver. NTSC receivers eventually were equipped with comb filters to separate the chrominance and luminance signals, but at the expense of some vertical resolution.

The low-visibility principle is applied not only to avoid luminance–chrominance cross-talk but also to reduce the effect of the beat between the 4.5-MHz sound carrier and the color subcarrier. To take advantage of the low-visibility principle, television standards were modified slightly when color television was introduced. The sound carrier remained the same at 4.5 MHz above the video carrier. The relation between the horizontal scanning frequency, f_{h}, and the color subcarrier frequency, f_{SC}, was picked to be $f_{\mathrm{SC}} = 227.5\, f_{\mathrm{h}}$. Then the sound subcarrier-minus-color subcarrier beat was likewise made an odd number of half-multiples of the horizontal scanning frequency: $4.5\,\mathrm{MHz} - f_{\mathrm{SC}} = 58.5\, f_{\mathrm{h}}$. Putting these two relations together determines the horizontal frequency, 15 734.264 Hz, and the color subcarrier frequency, 3.579 545 MHz. The number

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of scanning lines remained at 525 so the vertical frequency changed from 60 Hz to $262.5f_h = 59.940$ Hz. With these choices, the sound carrier is at 286 times the horizontal frequency. This would produce a high visibility pattern but the sound carrier is above the nominal video band and can be filtered out easily.

Color television receiver

The block diagram of Figures 19.7 shows the overall organization of an NTSC color television receiver. The first block is simply an AM radio receiver for VHF, UHF, and cable frequencies (about 52–400 MHz).

The carrier of the selected channel is translated to an IF frequency of 45.75 MHz and the IF bandwidth is about 6 MHz. The shape of the IF passband must be quite accurately set to equalize the vestigial sideband, to provide full video bandwidth, and to reject adjacent channels. This originally required careful factory adjustment of many *LC* tuned circuits but was later determined by the geometry in a single SAW filter. The IF signal contains the composite video (luminance and sync) plus the sound and color information. The sound and color signals, which are essentially narrowband signals around 4.5 MHz and 3.57 MHz, ride on top of the luminance signal. A 4.5-MHz bandpass filter isolates the sound signal in the block labeled “4.5-MHz FM Receiver.” FM stereo sound uses the demodulator described in Chapter 18. The sound subcarrier is at 31.5 kHz so that the oscillator in the demodulator can be synchronized to the horizontal sweep trigger at 15.75 kHz. A 4-MHz lowpass filter eliminates the sound signal from the video. The resulting video signal, the “*Y*” signal, contains the brightness information and would produce the correct picture if sent to a monochrome picture tube.

Chrominance processor

The 3.57-MHz color burst on the back porch of the horizontal sync pulses provides a reference for the phase locked L.O. in this QAM demodulator. Not shown on the diagram is an electronic switch, the burst gate, which is controlled by the synchronization circuitry to apply the reference signal only during the burst period in order to improve the signal-to-noise ratio of the loop. The local carrier is fed to a product detector (multiplier) to demodulate the *I* signal. A 90° phase shift network proves a second local carrier, shifted in phase for a second product detector to demodulate the *Q* signal.

Sync processor

A comparator, with its threshold set at the black level, strips away the video signal, producing a clean train of sync pulses. As explained above, a simple RC differentiator then provides horizontal reference pulses and an RC integrator provides vertical reference pulses. A VCO, phase-locked to the horizontal reference pulses, provides a flywheel stabilized horizontal time base. The VCO operates at twice the horizontal frequency and is divided by 2 to provide 15 734 Hz for the PLL phase detector and to drive the horizontal deflection

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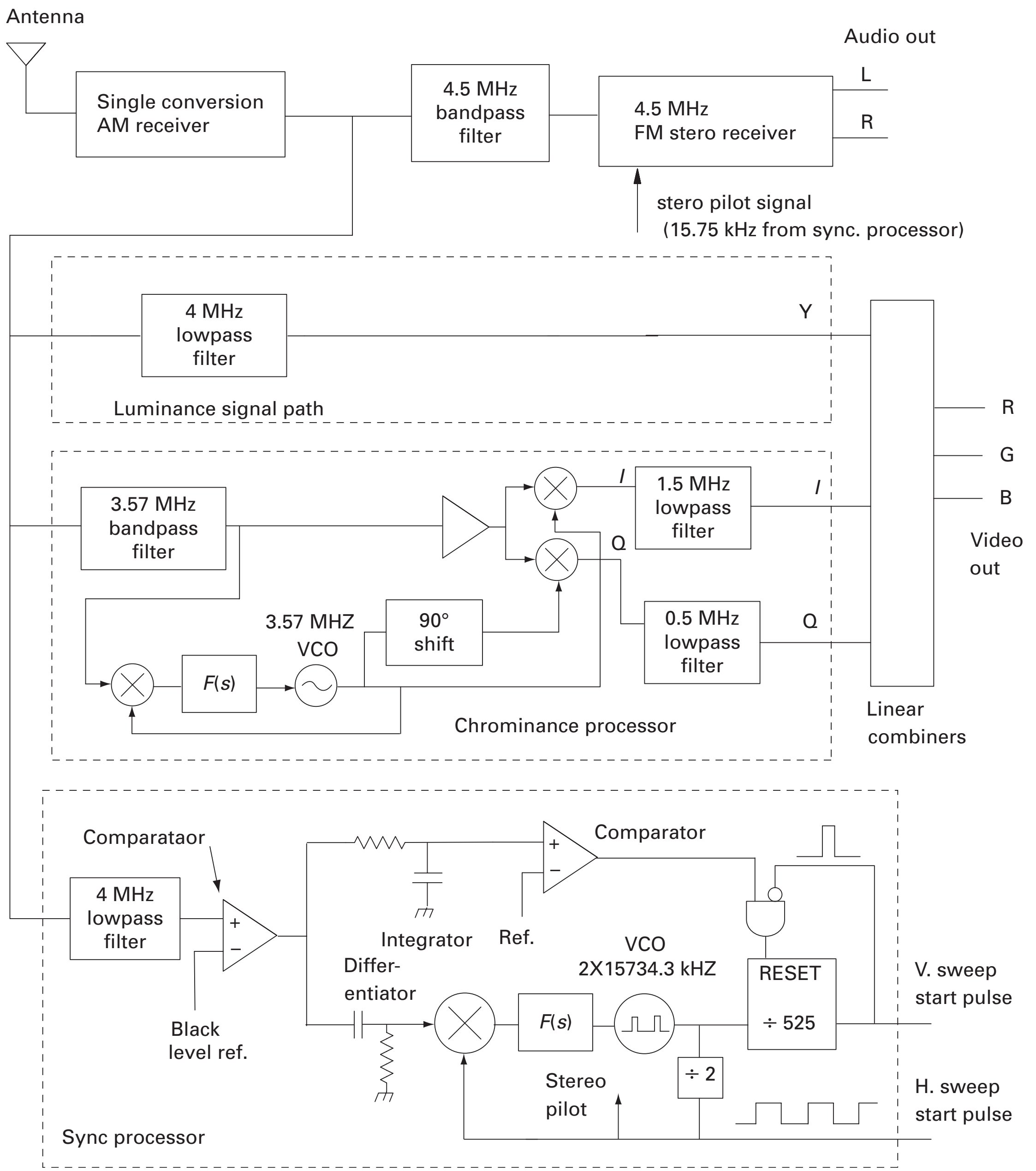

Figure 19.7. NTSC color television receiver block diagram.

circuitry. The VCO is also divided by 525 to provide an equally stable vertical time base. This divider must operate with the right phase for the picture to have the correct vertical alignment so the divide-by-525 counter has a reset input which will be triggered when the counter output has failed to coincide with several consecutive vertical reference pulses.

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19.3 Digital television

The first digital television broadcasting in the U.S. began in 1998, following the 1996 adoption by the Federal Communications Commission (FCC) of the system developed by the Advanced Television Standards Committee (ATSC). Television stations were assigned new channels for digital broadcasting but have also continued their NTSC analog broadcasts during the digital phase-in period which, at this writing, is scheduled to end in 2009.

The ATSC standard incorporates MPEG-2 program compression (itself a standard, ISO/IEC 13818), which is based on the temporal and spatial redundancy of the video program material.[2] MPEG-2 is also used for digital television in Europe (DVB) and Japan (ISDB), for direct television broadcasts from satellites, and for DVDs. Digital processing and storage make it possible to exploit the redundancies of the program material to compress up to six standard-definition (480-line) programs or at least two high-definition (720 or 1080-line) programs into the same 6-MHz wide channel needed for a single NTSC program. (The same redundancies are exploited to a much smaller degree in the NTSC system with its temporally-interlaced fields and its frequency-interleaved luminance and chrominance signals.) The net data rate for the ATSC system is 19.3 Mbits/sec through a 6-MHz channel, after overhead for error correction. Let us estimate how much compression is involved when four standard-definition programs with typical frame-to-frame motion are compressed down to a total bit rate of 19.3 Mbits/sec. We will assume these programs are in the "480i" format, where 480×704 pixels are transmitted at a 30-Hz rate. Let us further assume there are three 8-bit numbers, a luminance value and two chrominance values, for each pixel. The overall data rate would be four channels $\times\, 480 \times 704 \times 8$ bits $\times\, 3$(colors) $\times\, 30$ Hz $= 973$ Mbits/sec. Dividing by 19.3 Mbits/sec, the compression factor is 50.4. When audio is included in the calculation, the factor increases slightly.

Digital television uses a three-step process. First, the video and audio program material, in raw digital bit streams, is compressed to packet streams having much lower bit rates. The video and audio packets, together with packets of ancillary data and null packets (padding) are merged together to form a stream of *transport packets*, each one containing 187 data bytes. The packets have headers to identify the program (since a stream may contain several independent programs) and the type of packet: video, audio, or, ancillary information, or null. Second, the stream of packets is run through a two-stage forward error correction (FEC) encoder which adds redundant bits to each packet so that the receiver can detect and correct transmission errors caused by noise and

[2] The ATSC system does not use the audio part of MPEG-2 for audio, but instead uses AC-3 (Dolby digital) compression, which provides each program with up to five full audio channels plus a low-frequency subwoofer channel for "surround sound."

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interference. Third, the bits in the stream of expanded packets produce the RF signal for transmission. This signal is single-sideband suppressed-carrier AM (SSBSC) except that a vestige of the lower sideband remains (as in the NTSC standard) and the carrier is not completely suppressed; a pilot carrier is inserted as a reference for synchronous detection in the receiver. At the receiver, the three steps occur in the opposite order. The bit stream is demodulated from the RF signal. The FEC-encoded packets are then decoded, correcting transmission errors and producing the original packets of compressed data. These packets are then separated, according to program, and each program is decompressed into the original audio and video bit streams.

19.3.1 MPEG encoding

The picture is encoded (compressed) at the lowest level in blocks of eight pixels by eight pixels. (Note that "compression" and "decompression" of the program data are usually called coding and encoding, the same terms used for the processes used to anticipate and correct transmission errors.) Video usually has a high degree of spatial correlation, i.e., adjacent pixels tend to have similar brightness and color. When an ($n \times n$)-pixel picture is encoded using a two-dimensional discrete Fourier transform (DCT), the resulting coefficient matrix can be inverse-tranformed to exactly reconstruct the picture. But if the coefficients are coarsely quantized, i.e., rounded to use fewer bits before the inverse transformation, the reconstructed picture is found to retain most of its original quality.[3] Moreover, because of spatial correlation, these coefficients tend to concentrate in one corner of the coefficient matrix. Away from this corner, the coefficients have low values. Thus, a great many of the coefficients can be represented as zeros and the rest by numbers of only a few bits, so DCT encoding providing a significant amount of compression.

Except for scene changes, the differences from one frame to the next are mostly due to motion of elements within the picture (subject motion) or motion of the picture as a whole (camera motion). From frame to frame, a given block will therefore mostly just shift its position somewhat. In the ATSC system, for each 16×16 block (*macroblock*) in a new frame, the MPEG encoder determines the displaced macroblock in the previous frame that provides the best match by minimizing the sum of the absolute values of the differences of the pixel brightness values. The position of the displaced macroblock is specified by a *motion vector*, e.g., 1,1 would indicate that the best match macroblock is shifted one pixel up and one pixel to the right. These motion vectors are part of the video update information. The rest of the information consists of DCT-tranformed *differences* between the pixel values in these displaced "prediction" macroblocks and the new pixel values in the block being updated. At the

[3] The same principle is used for audio compression. Blocks of audio voltage samples are transfomed and the resulting coefficients are compressed and transmitted.

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encoder, the macroblock is subdivided into four 8×8 blocks, and the 64 pixel differences for each block which, again, have considerable spatial correlation, are transformed using an 8×8 DCT.[4] (It is computationally more efficient to transform small blocks, and the 8×8 size was found adequate to provide the desired compression.) When most of the coefficients in a transformed block are negligible, the resulting stream of digital numbers consists mostly of zeros, and run-length encoding (specification of the number of consecutive zeros) is used to increase the degree of compression. The number of consecutive zeros is increased by using a certain zigzag readout ordering of the coefficient differences. In addition, variable length coding is used for the nonzero transform differences; the viewer can tolerate coarser quantization for the high spatial frequencies.

Note that not all the frames can be predicted from previous frames; channel surfers need the picture to change promptly and, of course, a change of scene requires all-new data. Occasional *refresh frames* (tagged as such) are therefore inserted into the stream of prediction/correction frames. In a refresh frame, every block is transmitted. Between refresh frames, only changing macroblocks need to be transmitted. As in the NTSC system, the two color signals can have lower spatial resolution than the luminance signal, just as a black and white photograph can be "colorized" using a relatively broad brush. In the ATSC system, each of the two color elements has half the resolution (1/4 the number of pixels) as the luminance element, further compressing the video signal. The output from the MPEG encoder, together with the audio material, is a string of 188-byte packets: 187 data bytes plus one sync byte. Note that the packets are asynchronous; their lengths and mix is program dependent. Video and audio are both time-stamped so that they can be aligned by the decoder. After leaving the MPEG encoder, the bits in the 187 data bytes are "pseudo-randomized" by multiplication with the bits from a pseudo-random shift register sequence. This step, which is undone in the receiver, just ahead of its MPEG decoder, ensures that the spectrum is flat, even if the output of the encoder is interrupted, and makes it easier for the receiver to find the transmission packet sync byte which is added during the forward error correction encoding.

19.3.2 Forward error correction

The ATSC system applies two levels of forward error correction. "Forward" means that bits added in the encoding process make it possible to correct errors rather than simply detect them. Of course, this works only up to a limit; when the signal-to-noise ratio drops below a threshold, uncorrectable errors begin to produce visible artifacts and beyond this, the signal soon suffers total

[4] The DCT can be done by multiplying the (8×8) pixel or pixel difference matrix by an (8×8) transform matrix. The inverse of this matrix provides the inverse transformation. However, there are faster methods, analogous to the FFT algorithm for calculating the DFT.

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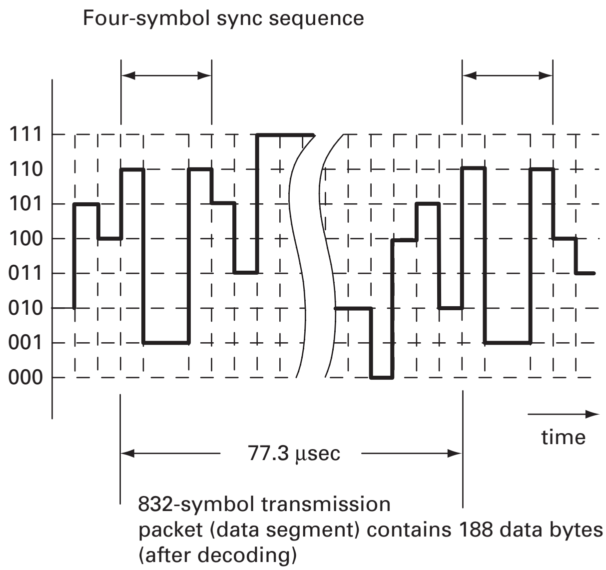

Figure 19.8. ATSC transmission packet.

degradation – the well known "threshold effect" in digital communication links. The bit-randomized MPEG packets are first processed by a Reed–Solomon encoder which adds 20 parity bytes to the 187 data bytes increasing each packet to 207 bytes. This Reed–Solomon encoding makes it possible to correct up to 10 defective bytes per packet, no matter how many bit errors these bytes contain. The next stage is an interleaving (shuffling) of bytes within blocks of 52 of the 207-byte packets. This interleaving makes it less likely that a wide noise burst will leave more than 10 bad bytes in any packet after de-interleaving has been done at the receiver. The second level of FEC encoding is a convolutional or trellis encoding, which is effective against white noise. The trellis encoder produces three output bits for every two input bits, bringing each packet up to $207 \times 3/2 \times 8 = 2484$ bits, or $2484/3 = 828$ three-bit (eight-level 8-VSB) symbols. The trellis encoding is a flow process; each bit triplet leaving the trellis encoder is calculated from only the last four pairs of input bits. Finally, a four-symbol sync sequence is added for a grand total of 832 8-VSB symbols per transmitted packet, as shown in Figure 19.8.

With the concatenated Reed–Solomon and Trellis error correction coding, the threshold of visibility for the ATSC system occurs at a S/N ratio of 14.9 dB. At this threshold, the data segment (832-symbol transmission packet) error rate is about 1.93×10^{-4} or 2.5 segment errors per second.[5] The FCC requires that over the area of service, a broadcaster's ATSC signal must exceed the threshold by 7 dB. Compared to NTSC, ATSC broadcasting requires less than 1/10 as much

[5] These numbers are taken from ATSC Document A/54A, "Recommended Practice Guide to the Use of the ATSC Digital Television Standard."

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transmitter power. (Nearly all the ATSC transmitted power bears information, while much of the NTSC power goes into the carrier and horizontal sync pulses.)

19.3.3 RF modulation

The three-bit symbols are converted by an A-to-D converter into an eight-level analog signal which amplitude modulates the carrier wave. The carrier is suppressed except for a low-amplitude pilot. Figure 19.9 shows a modulator circuit whose input is the stream of transmission packets, each containing 832 three-bit symbols, including the four-symbol segment sync. A filter eliminates all but a vestige of the lower sideband.

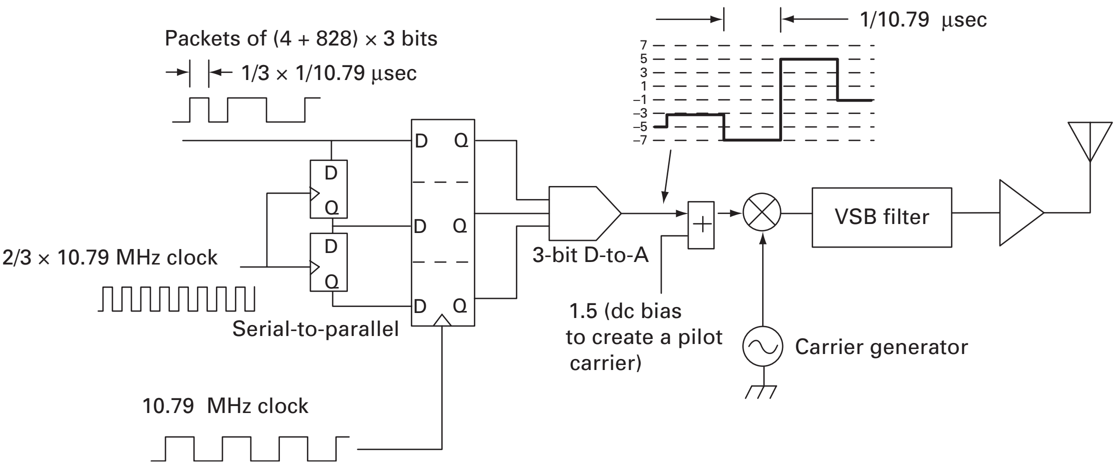

Figure 19.9. ATSC 8-VSB modulator.

Figure 19.10 compares the spectrum of an ATSC signal with that of an NTSC spectrum.

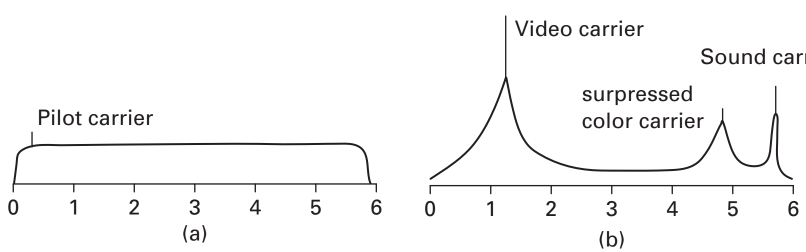

Figure 19.10. Comparison of the ATSC spectrum (a) and the NTSC spectrum (b).

19.3.4 HDTV receiver

The ATSC standard provides 18 different video formats, ranging from high-definition 1920 × 1080 pixels, interlaced with 60 fields/second or noninterlaced with 30 or 24 frames/second, down to 640 × 480 pixels, interlaced with 60 fields/second or noninterlaced with 60, 30, or 24 frames/second. The receiver

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identifies the video format being used and decodes the video. It then scales and interpolates the decoded image to produce a picture that fits the native resolution of the display screen, unless the program happens to match the native resolution. When the screen does not have the same aspect ratio (16:9 or 4:3) as the program, the receiver will produce a "letter box" display, with the picture between black horizontal strips, or a "keyhole" display, with the picture between black vertical strips, or the view may be able to opt for a distorted picture that fills the screen. Figure 19.11 is a simplified block diagram for an ATSC television receiver.

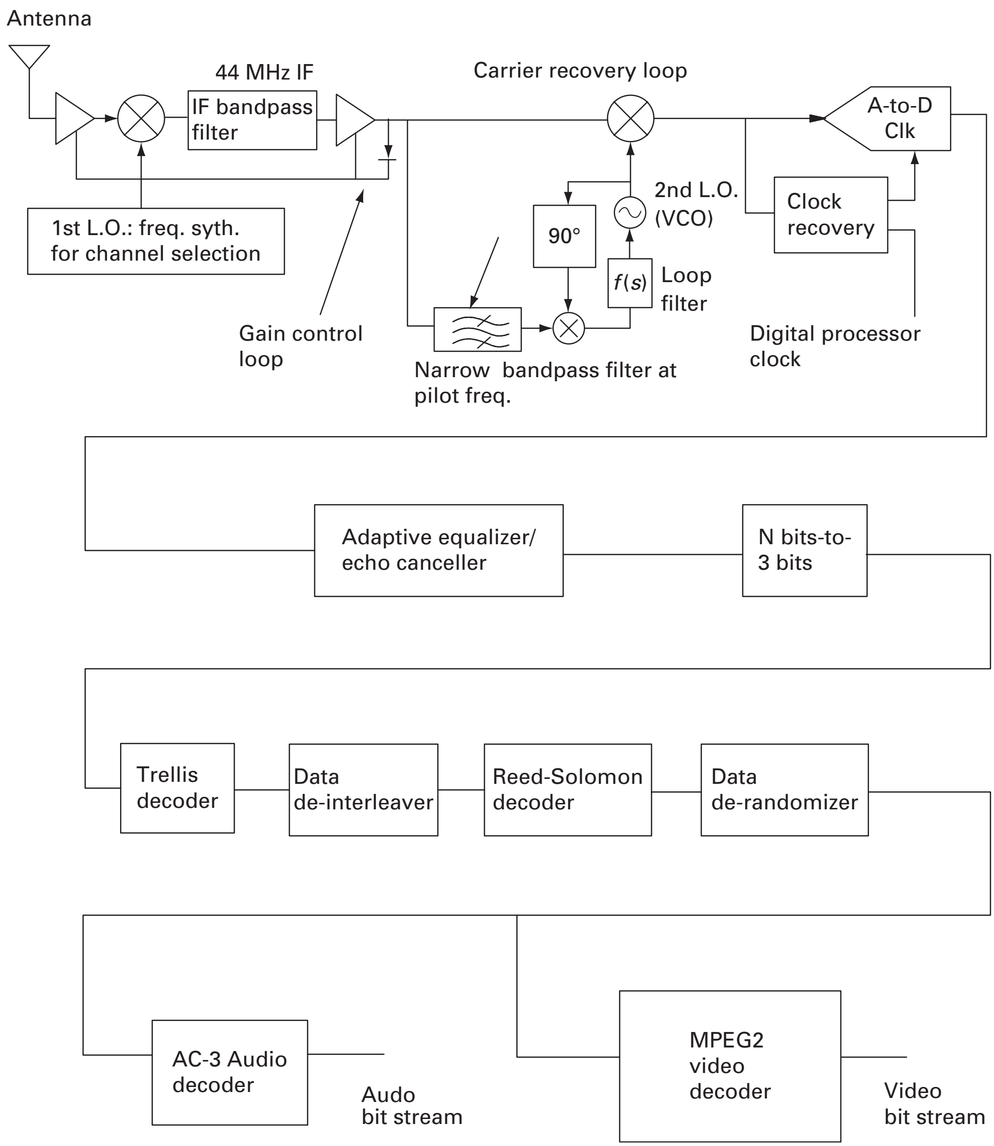

Figure 19.11. An ATSC television receiver block diagram.

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The conventional RF sections are all in the first row of blocks. The signal is first mixed down to a first-IF frequency, often around 44MHz. Just as in an NTSC receiver, the L.O. for the first mixer selects the channel. The amplified IF signal is synchronously detected by multiplying it by a sine wave at the carrier frequency. This sine wave is produced by a VCO referenced to the pilot carrier in a phase lock loop. Without the 90° phase shifter in the loop, the VCO output would be 90° out of phase with the pilot carrier and there would be no output from the synchronous detector. (If the consortium that developed the ATSC standard had opted for quadrature AM (QAM), there would have been two final mixers producing I and Q signals, rather than just a single mixer producing the I signal.) The detected signal, which is a zero-frequency IF "baseband" signal, is fed to an A-to-D converter. While the amplitude of the signal has nominally only eight levels (three bits), at this point it is still dithered by multipath echos and noise, so the A-to-D converter may have eight or ten bits. The clock rate of this converter may be a multiple of the symbol rate in order to recover the symbol clock with high precision. The clock recovery block finds the four-symbol segment sync sequence and phase locks the recovered symbol clock to it.

The equalizer is an adaptive filter which serves two purposes. It corrects the overall frequency response (transfer function) to minimize intersymbol interference (see Chapter 22) and it cancels echos – multipath interference. Both of these functions are essential in order to reproduce the transmitted signal well enough to distinguish one of eight possible amplitude values for each symbol. The usual form of the equalizer is a transversal FIR filter with programmable tap weights (amplitude and phase). The weighted outputs from the taps are summed to form the filter output. Every 313th transmission packet contains a "training" sequence, which is a reference waveform used by the receiver to determine the proper weights for the equalizer filter taps. Once the equalizer and the overall gain are correctly set, the signal can be sampled at the symbol rate $\times 1$ to reproduce the data stream shown in Figure 19.8. Subsequent processing steps then undo the various stages of encoding. A trellis decoder (Viterbi decoder) is followed by a block that de-interleaves the bytes. Then the Reed–Solomon encoding is decoded. Finally, the pseudorandom coding is undone and the data can proceed to the MPEG decoder, which outputs synchronized video and audio.

Problems

Problem 19.1. Suppose the NTSC signal from a television receiving antenna consists of the direct signal (via the line-of-sight path to the transmitting station) and a weak secondary signal (via reflection from a metal tower off the line-of-sight). If the path taken by the secondary signal is 1 km longer than the path of the direct signal, what will be the position of the "ghost" image on the screen of the receiver?

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Problem 19.2. Motion pictures from film shot at 24 frames/second are transmitted as 60 field/second television images using a technique called *3:2 pull down*. A film frame is held in place while two television fields are transmitted. The subsequent film frame is then pulled down and held in place while three television fields are transmitted. Show that this scheme results in an average film rate of 24 frames/second.

Problem 19.3. Consider a high-definition television monochrome signal with 1920×1080 pixels and progressive scan (no interlace) at 60 frames/sec. If the brightness of each pixel is specified by an 8-bit number, and if no compression is used, what is the data rate? Answer: 995 Mbps. What compression ratio is needed if this signal is to be transmitted over a standard width television channel at a rate of 19.3 Mbits/second?

Problem 19.4. Suppose an NTSC test pattern consists of five vertical bars of equal width but different colors. Let the bars all have the same luminance (brightness) and be only lightly colored (unsaturated). Sketch the waveform for one line of video.

Problem 19.5. Interlaced scanning provides more resolution for fixed scenes but can produce artifacts with moving objects. Think of a situation where interlaced scanning could make a moving object vanish.

Problem 19.6. Shannon's channel capacity theorem states that data, if suitably encoded for error correction, can be sent with an arbitrarily low error rate if the net data rate (bits/sec.) does not exceed the channel capacity, given by $C = B\log_2(1+S/N)$. Compare the ATSC bit rate, 19.3 Mbits/second with the theoretical capacity of the 6-MHz channel at the threshold S/N ratio of 14.9 dB.

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