

TELEVISION GOES DIGITAL

Once upon a time, entertainment meant getting out of the house for an evening at the movies, a trip to the ballpark, or a visit to the concert hall. But eventually entertainment followed us home and settled itself in our living rooms and dens. Community life has never been the same since. And although we may lament the isolation and loss of shared experience that have accompanied this boom in home entertainment, it's hard not to admire the science and technology behind it.

There are two problems involved in trying to describe the scientific basis for home entertainment. First, home entertainment is a topic that has fuzzy edges and means different things to different people. Although I personally find mowing the lawn entertaining, I'll concede that yard work offers less in the way of interesting physics than do television and its related hardware. So this article focuses on the science and technology of analog and digital TV transmission, and in particular on the most spectacular digital standards, known as high-definition TV, or HDTV (figure 1). (I don't have room here to cover the evolving audio system technologies.) Second, TV technology is changing so quickly that it's hard to keep up. Standards evolve, schedules change, new innovations explode onto the market almost overnight. So this discussion is at best a passing snapshot, one that will probably seem like ancient history a decade from now.

Analog TV

One of the most impressive aspects of the ongoing digital TV revolution is that it is taking place on top of the complicated, well-established infrastructure of analog TV. The two systems, while not directly compatible with one another, will coexist long enough for an almost painless, gradual migration to digital. Moreover, this shift is being accomplished with few serious long-term compromises to the digital standard. Although analog TV sets can't directly decode the digital transmissions and will display only flurries of those transient flecks popularly known as snow when you tune to a digital channel, these sets won't be instantly obsolete. Set-top converter boxes are available that receive the digital transmissions and deliver them to TV sets in analog format. Although this hybrid approach does not provide the full resolution of digital video, the picture is still considerably sharper than with ordinary analog reception. This sort of open-heart surgery on the TV infrastructure happened once before, when color TV joined

The new technology is bringing images of unprecedented clarity into our homes by exploiting the existing bandwidth and pushing signal-to-noise ratios almost to their theoretical limits.

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black-and-white back in the mid-1950s. In fact, examining that earlier revolution and the basics of analog TV makes it easier to understand the transition to digital.

The images that you see on a conventional TV screen, whether color or black-and-white, are produced by glowing phos-

phors that coat the inside surface of the picture tube (figure 2). These phosphors are excited one dot at a time by a focused beam of 25 keV electrons emerging from a gun at the back of the picture tube. Electromagnetic coils on the tube's neck deflect the electrons and sweep the beam across the screen in a raster fashion, starting in the upper left corner. The beam sweeps horizontally to the right edge of the screen and then snaps back to the left to begin its sweep again. With each new horizontal sweep, the beam shifts lower on the screen until eventually it reaches the bottom edge. It then snaps back to the top and starts its work all over again.

As the electron beam sweeps across the screen, a control grid in the tube's electron gun modulates the electron intensity. To produce dark spots, the grid voltage is lowered so that it pinches off the flow of electrons and prevents them from reaching the phosphors. To produce bright spots, the grid voltage is raised and the electron beam intensifies. By carefully synchronizing these brightness variations with the horizontal and vertical sweeping processes, the TV set produces clear images on its screen.

The slow optical response of our eyes prevents us from seeing this image-building process, and the rapid sequencing of those images gives the appearance of seamless motion. In the US, the National Television Systems Committee (NTSC) standard specifies 60 partial images per second in interleaved pairs having a combined total of 525 horizontal lines. The first image, or "field," in each pair contains only the odd-numbered lines, while the second field contains only the even lines. The first 20 lines of each field aren't visible, occurring while the electron beam is returning to the top of the screen, so the first field contains lines 41, 43, . . . , 525, while the second field contains lines 42, 44, . . . , 524. The number of dots per line is limited by the bandwidth of the video signal, but rarely exceeds 440. Thus, NTSC video forms complete images (both fields) of roughly 213 400 dots (485 visible lines with 440 dots per line) at a net rate of 30 images per second.

The NTSC monochrome video signal contains both brightness and synchronization information, a combination known as composite video. Each brightness level is represented by a particular signal voltage, so that temporal patterns of voltage on an input wire produce spatial patterns of light and dark on the screen. Since this voltage



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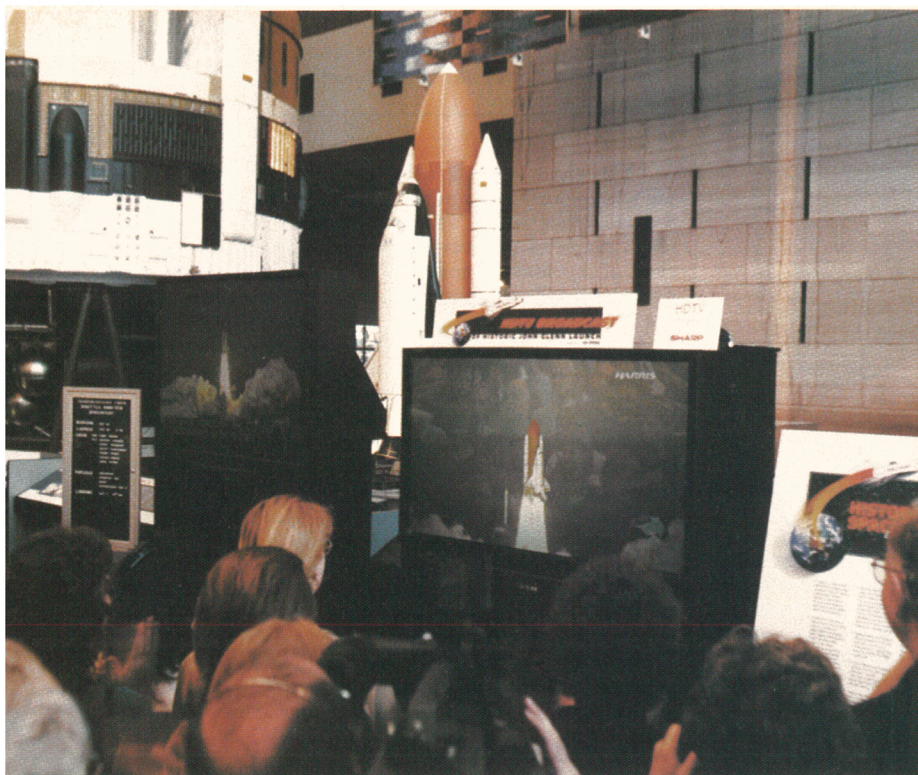


FIGURE 1. DIGITAL TELEVISION. Visitors to the Smithsonian Institution's National Air and Space Museum in Washington, D.C., witness John Glenn's historic return to space on a wide-screen digital TV set. With its ten-fold better resolution, 16:9 rather than 4:3 aspect ratio, and freedom from visual and audio noise, this 64-inch high-definition TV set leaves little interest in the conventional analog set to its left. (Photograph courtesy of Harris Corporation.)

ultimately controls the grid in the picture tube's electron gun, negative-going voltage excursions darken the screen. To synchronize the horizontal and vertical sweeping processes, the signal makes brief excursions below the voltage representing full black. One of these "blacker than black" pulses precedes each horizontal sweep, and a string of such pulses precedes each vertical sweep.

Television developed in a broadcast environment that put strict constraints on bandwidth. When portions of the precious electromagnetic spectrum were set aside for TV in 1941, the FCC gave each channel only 6 MHz to carry both video and audio signals. The transmission scheme adopted by the NTSC involves two separate RF carriers, one for video and one for audio. Video information occupies the lower 5.25 MHz of the channel bandwidth, while audio occupies the upper 0.75 MHz (figure 3).

The video carrier is amplitude modulated by the video signal, a process that produces sidebands on either side of the carrier frequency. Because each sideband contains the same information, transmitting both would be a waste of bandwidth, and so most of the lower sideband is filtered away. The final video portion of the TV transmission extends no more than 1.25 MHz below the video carrier and 4 MHz above it, an arrangement known as vestigial sideband (VSB) modulation. The 4 MHz cutoff of the upper sideband is necessary to leave room for the audio signal, but it significantly limits the horizontal resolution of broadcast TV images. Also, the large DC component of the video signal produces a peak in the modulated signal power at the video carrier frequency. This intense carrier emission consumes a significant fraction of the transmitted power and presents a serious interference problem for digital TV during the analog/digital coexistence period.

The audio carrier, located 4.5 MHz above the video carrier, is frequency modulated by the audio signal and transmitted with both of its sidebands intact. The techniques used are identical to those of FM radio: The audio

signal typically contains two separate channels transmitted simultaneously to deliver stereo sound. Below 15.734 kHz (15.750 kHz in the days before color TV), the audio signal contains the sum of voltages from the left and right microphones. Above 15.734 kHz, the signal carries a frequency-upshifted version of the difference between the two voltages. An inaudible tone, or "pilot," at 15.734 kHz marks the presence of the upper channel and provides the frequency and phase reference needed to downshift that channel back to its normal frequency range.

Although a simple TV set with one speaker will extract only the sum signal below 15.734 kHz, a stereo set will decode both the sum and difference signals to obtain separate audio for its left and right speakers.

The addition of color

With video information occupying a channel's lower 5.25 MHz and sound information occupying its upper 0.75 MHz, the 6 MHz of allocated spectrum appears full. Yet, in late 1953, the NTSC established a color video standard that shoehorned color information into this already crowded space. Moreover, the committee did it in a way that let existing black-and-white sets continue to work.

The NTSC took advantage of a comb of holes in the monochrome, or "luminance," signal's frequency spectrum. Because adjacent horizontal lines are usually pretty similar, many features of the luminance signal recur at the horizontal sweep rate. That rate was 15 750 Hz in the days of black-and-white TV but, as we'll soon see, is now 15 734 Hz. As a result of this repetition, most of the spectral power in the luminance signal appears at or very near the harmonics of 15 734 Hz. The regions of frequency space between these harmonics are essentially empty because they represent the unlikely cases in which adjacent horizontal lines contain brightness features that are exactly opposite to one another.

Into this comb of quiet regions in the luminance signal, the NTSC inserted the chrominance signal (figure 3). They placed a chrominance subcarrier halfway between the 227th and 228th harmonic of the horizontal sweep rate and modulated this carrier in both amplitude and phase with the two additional video signals needed to create full-color images. The two new signals joined the luminance signal in controlling the three primary colors of light—red, green, and blue—and were mapped in such a way that luminance still represented brightness and chrominance represented color deviations away from whiteness. Thus, a

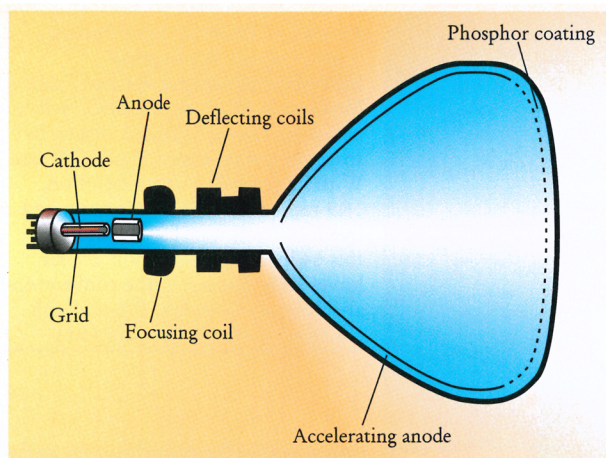


FIGURE 2. MAIN COMPONENTS of a black-and-white picture tube. The trajectory of an intensity-modulated electron beam is controlled by electric and magnetic fields whose sources are positioned as shown.

TV set detecting only the luminance signal still displays a normal black-and-white picture.

To provide the phase and amplitude reference that a set needs to demodulate the new chrominance signals, a pulse of unmodulated chrominance subcarrier is transmitted during the brief interval between the horizontal sync pulse and the actual start of the horizontal sweep. Together with the set's tint and hue controls, which are actually phase and amplitude adjustments, this "color burst" allows the set to achieve proper color balance.

The luminance and chrominance power spectra interdigitate perfectly and share the channel's frequency space with almost no noticeable effects on one another. This spectral sharing is aided by the fact that our eyes are less sensitive to color detail than to brightness detail, so that the NTSC was able to limit the chrominance bandwidth to just 1.5 MHz below and 0.5 MHz above its subcarrier.

However, because everything around the video carrier is demodulated as luminance signal and everything around the chrominance carrier is demodulated as chrominance, a TV set routinely misinterprets some chrominance information as luminance information and vice versa. These misinterpretations produce high-spatial-frequency checkerboard patterns on the screen. Fortunately, the checkerboards are hard to notice even if they stand still. But because of the odd number of lines (525) in a complete image, the checkerboard pattern in one image is reversed in the next, and the pattern quickly averages its way to invisibility.

To form color images on its screen, a TV set adjusts the brightness of red, green, and blue phosphors on the inside of the screen. The phosphors are arranged as tiny dots or lines that are so closely spaced that our eyes merge their lights together so that we see full-color images. But directing one electron beam accurately enough to hit specific patches of colored phosphor is hard, so a color picture tube places a shadow mask just behind its screen. The metal mask contains a pattern of tiny holes or slits that cast shadows on the screen and allow electrons from only a specific direction to hit the red phosphor patches. Electrons from a second direction can hit the blue phosphors, and from a third direction can hit the green phosphors.

The color picture tube forms three separate electron beams and arranges their flight paths so that each beam illuminates only one color of phosphor. The "red" beam hits only the red phosphor spots, the "green" beam hits only green phosphors, and the "blue" beam hits only blue phosphors. By controlling the intensities of the three electron beams, the TV set selects the color we see when we look at each location on the screen.

The shadow mask must conduct electricity, tolerate high temperatures, and remain in perfect registry with the phosphor spots. The only reasonable choice for the mask material is Invar, a steel alloy with a small coefficient of thermal expansion. Unfortunately, Invar is easily magnetized. Because a magnetized shadow mask deflects the electrons passing through it, causing beautiful but undesirable color shifts, many color sets and monitors have automatic degaussing coils in them.

The only other change needed to accommodate color in 1953 was a slight shift in the NTSC frequency specifications. To avoid beating problems between the audio and chrominance carriers, the horizontal sweep rate was decreased 0.1% from 15 750 to 15 734.264 Hz. This tiny shift made the 4.5 MHz frequency spacing between the audio and video carriers equal to the 286th harmonic of the horizontal sweep rate and brought the 3.579545 MHz chrominance subcarrier into phase lock with those other two carriers. No more beating! As a side effect, this change reduced the number of fields per second from 60 to 59.94. Fortunately, existing black-and-white sets tolerated such changes without a hitch, and for nearly 50 years NTSC analog color TV has dominated the airwaves in the US.

Why shift to digital TV?

Despite its elegance and maturity, analog TV is too limited to survive in this digital age. Low resolution, poor power efficiency in transmission, and a sensitivity to noise and interference are all contributing to its demise. Digital TV has none of these shortcomings and offers some amazing bonuses as well.

Analog TV's resolution problem stems from its absence of memory: It squanders bandwidth by transmitting redundant information. Because every dot is drawn the moment its information arrives at the set, there is no opportunity to use correlations in the information to reduce the required bandwidth. In contrast, digital TV uses sophisticated compression techniques to find and exploit temporal and spatial patterns in the images. Redundant information is squeezed out of the data stream, and extensive buffering prevents bursts of high data demand from overloading the transmission system. As a result of this compression, asynchronous operation, and load averaging, the same information bandwidth that supports low-resolution analog TV can support much higher resolution digital TV.

Analog TV's power inefficiency is inherent in the nature of its analog signals and the modulation techniques used to broadcast those signals. A large fraction of the transmitted power appears in its carriers and in the useless partial lower sideband of the video signal. Moreover, because its frequency spectrum contains many peaks and valleys, analog transmission is more easily damaged by white noise than it would be if its spectrum were smoother. In contrast, the spectrum of digital transmission is essentially flat, puts minimal power in its carrier, and even uses the band edges themselves to convey information.

Analog TV's sensitivity to noise and interference is typical of all analog systems: They're unable to distinguish noise in the physical quantity representing information from the information itself. Electrical noise in the video signal appears immediately on the screen as visual

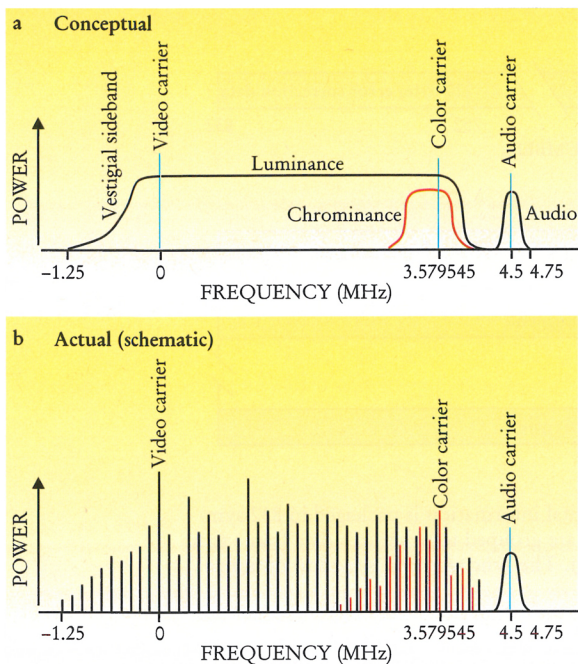


FIGURE 3. ANALOG TELEVISION SIGNAL fills a 6 MHz channel with brightness (luminance), color (chrominance), and audio information. Although the two video components appear to overlap (a), the luminance signal's power is concentrated at harmonics of the 15 734.264 Hz horizontal sweep frequency. By inserting the chrominance signal's power in between those harmonics (b), the two are kept from interfering with one another.

noise—snow, tick marks, and patterns are common. Likewise, delayed reflections of the signal itself produce ghost images.

Digital TV is much less sensitive to noise, because imperfections in the signals passing through the front end of the receiver can be completely and reliably removed before they have any effect on the displayed images. By using quantized values for the physical quantities conveying information, the digital approach prevents low-level noise on those physical quantities from affecting the information. With the help of error correction and digital filtering, digital TV is able to display perfect images even when the electromagnetic signals reaching the set have a fair amount of noise in them.

Digital TV technology

Whereas analog TV deals with images dot by dot in real time, digital TV treats the images as just another form of data to be compressed and sent through a high-speed communications channel. Compressed sound information uses the same channel. Because synchronization is achieved by decoding data at the proper rate, data transfers need not occur exactly in real time. This flexibility makes it possible to average out the load on the channel so that the channel is used with maximum efficiency. Everything you see or hear passes through the channel, so that channel now becomes the focus of our discussion.

In the US, the specifications for digital TV are set by the Advanced Television Systems Committee (ATSC), based on the work of a group known as the Grand Alliance. Under the ATSC standard, the same 6 MHz channels that have been carrying analog signals for decades can now carry digital signals. Each digital channel carries 10.762 megasymbols per second, where a "symbol" is a digit in the numerical base used by the channel. In binary systems (base 2), there are only two different symbols, 0 and 1, but digital transactions don't have to be in binary. The ATSC decided that cable TV can use hexadecimal (base 16) symbols and that terrestrial broadcast TV will use octal (base 8) symbols. It's still digital, but now each symbol is carrying more than one bit of information.

The symbols are encoded as different quantized amplitudes of an electromagnetic carrier. Because noise makes it hard to distinguish two closely spaced amplitudes, the size of the symbol group is limited by the signal-to-noise ratio at the receiver. With its goal of less than one unrecoverable data packet error per second, ATSC found that it needed a signal-to-noise ratio of 28.5 dB for base-16 transmission, and 22.3 dB for base-8 transmission. Although the base-16 requirement is widely achievable with the present cable TV infrastructure, the terrestrial broadcast environment is too noisy for true base-8 transmission. Instead, a third of the information in each symbol is sacrificed for error reduction in a technique known as trellis coding. Although eight different amplitudes are used to represent the symbols, each symbol provides only two bits of nonredundant information. The other bit is actually error correction information, dispersed in time so as to make the whole channel less vulnerable to white noise. Because of trellis coding, digital terrestrial broadcast TV can function reliably at a signal-to-noise ratio of only 15.0 dB. However, with twice as many bits per symbol (four versus two), digital cable can provide better images or even two high-definition TV programs on the same channel.

Digital broadcasts begin by digitizing and compressing the video and audio signals. Apart from analog-to-digital conversion issues, these steps are mostly mathematical, and I won't dwell on them here. The video compression involves the Moving Picture Experts Group MPEG-2 standard, and the sound compression uses the Dolby AC-3 standard. Although MPEG-2 compression loses some image information, compression by a factor of 10 is typically imperceptible and by a factor of 60 is usually quite acceptable. Following compression, the picture and sound are just packets of data that must be transferred to the viewer's TV set.

MPEG-2 video is divided into 188-byte packets. For transmission, a synchronization byte is removed from each packet and the remaining 187 bytes are sent through a "randomizer." This device scrambles the data in such a way as to produce a more even distribution of transmitted symbols and a flatter transmission spectrum. Then 20 bytes of Reed-Solomon (RS) error correction data are added. (See figure 4.) The resulting 207 bytes contain enough spare information to repair up to 10 damaged bytes per packet, regardless of where the damaged bytes are or how many bit errors each one has.

This error correction capacity makes digital TV reception extremely reliable, even in places where analog reception is marginal. To make the transmission even less vulnerable to brief transmission interruptions, bytes are exchanged between packets in an interleaving process that follows the RS coding. Because of this interleaving, extensive damage to a single packet won't necessarily lead to any loss of data.

The 207-byte information packets are transmitted in 832-symbol segments. For terrestrial broadcast, one packet occupies 828 symbols ($828 \text{ symbols} \times 2 \text{ bits per symbol} = 1656 \text{ bits}$, or 207 bytes) and is preceded by 4 synchro-

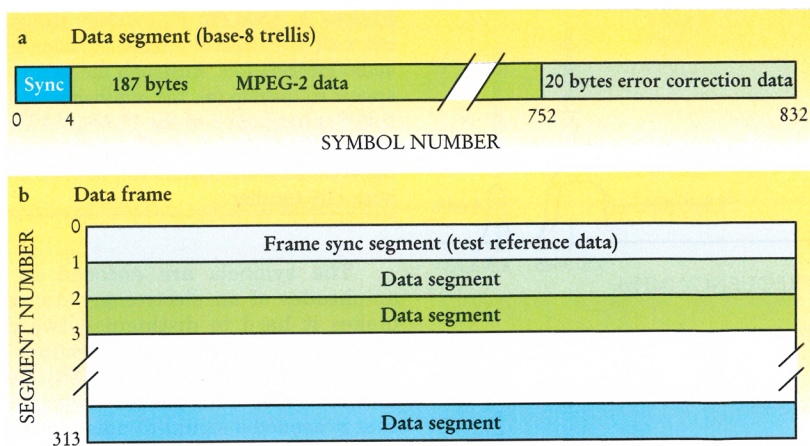


FIGURE 4. DIGITAL DATA FORMAT. (a) Digital information is packaged in 832-symbol data segments. (b) 312 of these segments are grouped together in a data frame that begins with a frame synchronization segment. The sync segment is used to optimize reception.

nization symbols. For cable transmission, two packets occupy 828 symbols ($828 \text{ symbols} \times 4 \text{ bits per symbol} = 3312 \text{ bits}$, or 414 bytes) and are preceded by 4 synchronization symbols. The data segments are transmitted one after another, with a special frame sync segment preceding every 312 data segments. This frame sync segment contains information about the transmission format (base-16, base-8 trellis, and so on) and several reference sequences that receivers use to adjust their digital filters for optimal reception.

At this point, the symbols are ready for transmission. The technique used to squeeze them into a 6 MHz channel is again VSB modulation. However, in digital transmission, the carrier itself is virtually absent and the high-pass filter that cuts off the VSB signal's lower sideband actually starts its work slightly above the carrier frequency (figure 5). This sharp filter allows the carrier to be placed only 0.31 MHz above the bottom of the channel, while leaving enough power in the cutoff region to permit accurate demodulation of the low-frequency information. The arrangement approaches the theoretical limit in its conservative use of bandwidth and power to maintain a high, uniform signal-to-noise ratio at all signal frequencies. An equivalent low-pass filter cuts off the high-frequency edge of the transmission only 0.31 MHz from the top of the band. Overall, 89.7% of the available bandwidth is used.

In keeping with the digital approach, the VSB carrier is amplitude modulated by the symbols, with each symbol corresponding to a specific amplitude. The symbol amplitudes are evenly spaced and extend from full positive amplitude, through zero, to full phase-reversed, or "negative," amplitude. For example, the eight symbols of base 8 are represented by the amplitudes 7, 5, 3, 1, -1, -3, -5, and -7. The symmetric distribution of amplitudes about zero, together with the flat distribution of symbols in the "randomized" data, is what eliminates the carrier from the modulated signal. There simply isn't any DC component in the sequence of symbol amplitudes. In fact, a small DC offset has to be added to the symbol amplitudes to create a small, in-phase pilot carrier signal within the transmission. This pilot carrier provides the positive phase reference a receiver needs to demodulate the transmission and recover the symbols.

After passing through the low- and high-pass filters, the VSB signal enters the transmitter and is distributed

through space or cable to TV sets in the surrounding area. Because the signal has a broad, flat spectrum, it uses the transmitter power with almost ideal efficiency.

To decode this signal, a receiver's local oscillator must lock onto both the frequency and the phase of the pilot carrier so that it can demodulate the RF and recover the sequence of symbols. Once the local oscillator is locked, the receiver begins searching the demodulated signal for segment sync symbols. It uses these sync symbols to lock its symbol clock so that it can collect each symbol at the proper instant.

But the symbols aren't obtained directly from the demodulated signal. Instead, at each tick of the symbol clock, a 10-bit digital-to-analog converter in the receiver makes a precise measurement of the instantaneous signal amplitude. The stream of measurements then passes through two sophisticated digital filters, which remove the effects of NTSC interference and transmission impairments so that when the measurements are finally converted into symbols, the assignments are more likely to be correct.

The first digital filter is especially good at eliminating the three carriers of analog TV, a critical task when a distant analog station is sharing the same 6 MHz channel. This preliminary filtering is done by delaying the sequence of measurements by 12 symbol times and then subtracting the delayed measurement from the current measurement. The procedure creates a comb filter with nulls in its transfer function at multiples of 1/12th the symbol rate or every 896.85 kHz. A careful choice of the digital carrier frequency places the filter's first null near the analog station's video carrier frequency, the fifth null near its chrominance subcarrier frequency, and the sixth null near its audio carrier frequency. The digital transmission itself is precoded using the same modulo arithmetic so that the filtering has no overall effect on it. The analog interference is almost perfectly removed, but the digital information remains! Though essential at present, this NTSC comb filtering will be switched off and abandoned when analog TV disappears.

The second digital filter consists of an equalizer, which eliminates interference due to reflections in the transmission path, and a phase tracker, which corrects for residual phase noise in the demodulation process. The coefficients of both components are adjusted by studying

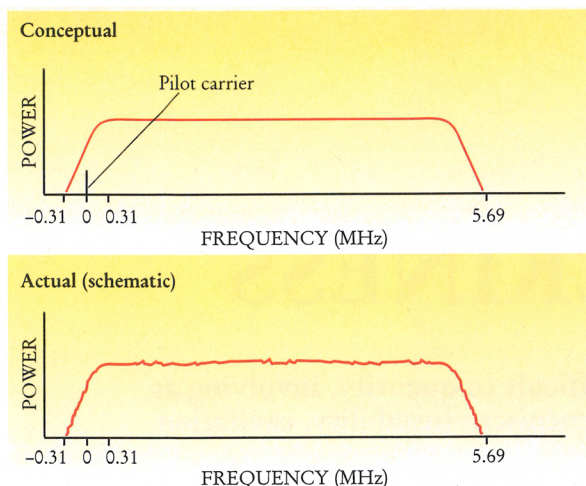


FIGURE 5. DIGITAL TELEVISION SIGNAL uses the 6 MHz channel almost to its information limit. The cutoff of the lower sideband begins above the carrier; even the power in the vestige of that lower sideband is used to convey information.

the signal amplitude measurements themselves, particularly those obtained from the reference sequences of the frame sync segments. Because this filter is continually optimizing its own performance, even fluttering airplane reflections can be removed.

The filtered amplitude measurements are finally sliced into symbols: Each measurement is assigned to the symbol with the nearest amplitude. This slicing is done directly for cable TV or with the help of a trellis decoder for terrestrial broadcast. The symbols are then deinterleaved into their proper segments, have any errors corrected by the Reed-Solomon decoder, and then pass through a "derandomizer" that undoes the initial "randomization." With the 187-byte data packets fully restored, they can be reassembled back into MPEG-2 video and AC-3 audio. It's showtime, folks.

The presentation process is pretty straightforward—the MPEG-2 and AC-3 decoders are just special-purpose computers, and the screen is simply a computer monitor. Because digital TV decouples transmission from presentation, the image resolutions and display rates can vary according to need. The ATSC standards include image resolutions up to 1080 lines with 1920 dots per line, for a total of 2 073 600 dots per image—about ten times the resolution of NTSC analog TV—and screen aspect ratios of both 4:3 (conventional) and 16:9 (wide-screen). The image rates include not only the nominal 30 Hz and 60 Hz standards of NTSC, but also the 24 Hz standard of motion picture film, so that movies and the many TV shows recorded on film can be displayed at their best. Finally, the sound system is a huge improvement over stereo, delivering up to 5.1 audio channels: left, right, center, left rear, right rear, and a special low-frequency effects channel (the extra 1/10th of a channel). So even if there's nothing worth watching, what there is will sure look and sound good.

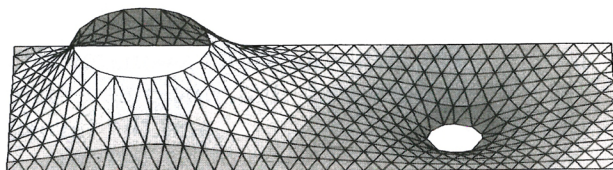
Suggested reading

- ▷ A. M. Noll, *Television Technology: Fundamentals and Future Prospects*, Artech House, Norwood, Mass. (1988).
- ▷ J. C. Whitaker, *DTV: The Revolution in Digital Video*, 2nd ed., McGraw-Hill, New York (1999).
- ▷ Zenith Corp's technical papers on high-definition television, available on the Web at <http://www.zenith.com> (click on "HDTV" and then on "Technical Papers"). ■

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