Chapter

13

Transmission

13.1 DTV Transmission

This chapter is what ATSC, in the purest sense, is all about. ATSC uses 8-VSB as a modulation scheme. This modulation scheme, like QAM, COFDM, QPSK, and others, allows transmission of digital data. The modulation schemes are not digital in nature; they just lend themselves to propagating digital information.

13.1.1 DTV channel assignments

The FCC's sixth report and order was issued on April 3, 1997. It was the initial DTV channel allocation table. Less than 10 percent of the DTV stations were issued VHF channels. This report also mandated that network affiliates in the top 30 markets must be on the air by May 1999. Six months after, all the affiliates in the top 30 markets must be signed on, and by May 2002 all commercial stations must be up and running. Noncommercial stations got an extra year to implement their DTV plans. The sixth report and order initially mandated that NTSC transmissions cease in 2006, but the Budget Reconciliation Act of 1997 modified that rule to allow for NTSC transmissions to continue until 85 percent of the television households in a given market could receive DTV signals. The order also stipulated that by April 2003 DTV stations must air 50 percent of the same programming as the NTSC channel. The simulcast required goes up to 75 percent the next year, and all NTSC programming must be available on the DTV channel by May 2005.

The station assignments are as follows: 943 UHF moving to UHF, 630 VHF moving to UHF, and 49 UHF moving to VHF.

The FCC used the grand alliance guidelines in assigning DTV power for each station 12 dB below the station's NTSC power level for UHF to UHF transitions. The FCC didn't use this guideline for conversion of VHF to VHF. The difference in power between NTSC and DTV is due to the signal-to-noise ratio between NTSC (-28 dB) and DTV (-15 dB), which is about 13 dB.

Moving from VHF to UHF requires great increases in radiated power because the FCC has increased its time factor from FCC (50,50) to FCC (50, 90) for replicating their grade B coverage. Low-frequency NTSC has large grade B zones due to the large diffraction zone at low frequencies. UHFs tend to have slightly larger grade As due to much higher power but significantly smaller grade Bs.

$$\text{Channel 4 grade A} \geq 68 \text{ dB}\mu$$

$$\text{Grade B} \geq 47 \text{ dB}\mu$$

$$\text{Channel 26 grade A} \geq 74 \text{ dB}\mu$$

$$\text{Grade B} \geq 64 \text{ dB}\mu$$

VHF signals can extend somewhat beyond the horizon because the VHF signal is diffracted along the curvature of the earth. The diffraction zone for UHF is about one-third that of VHF. VHF has good penetration into houses and buildings. The VHF signal propagates well beyond the optical horizon. Height is still important. At UHF frequencies the signal's optical and radio horizons are nearly the same. This means that UHF requires lots of power and antennas perched at high elevations to match VHF propagation. Channel 7 is probably the best rf channel. Low channels like channel 2 see a lot of skip, which causes cochannel interference. These low channels are also susceptible to RFI, EMI, and motor noise. Also, the channel bandwidth–to–actual frequency ratio is much wider; therefore, it is harder to set up good bandpass characteristics.

The core DTV spectrum is 2 to 51; any stations with assignments outside the core will have to vacate the new DTV assignment and go back to their original NTSC channel when NTSC goes dark. A few NTSC stations that are now outside the core have been assigned DTV channels that are also outside the core. It is yet to be determined what channel reassignment they will undergo when the transition is over.

DTV coverage is not protected beyond the existing NTSC grade B contour. The DTV service contours are as follows:

Channels 2 to 6—28 dBμ

Channels 7 to 13—36 dBμ

Channels 14 to 69—based on {41 + 20 log[615/(channel midfrequency)]}

The major concern is DTV's interference with NTSC stations. DTV is expected to be robust enough to withstand NTSC interference, but DTV interference into NTSC will mostly appear as increased noise in the video. As such, although new DTV channels are placed nearer existing NTSC cochannel stations than a new NTSC would be, some channel DTV stations are placed much closer to each other. NTSC interference into DTV and DTV interference into DTV have no protection.

Back when television receiver technology was young, many taboos existed as to the assignment and spacing of UHF channels. The restrictions were a result of limitations in the rejection of unwanted signals in the receiver. The UHF NTSC taboo channels were:

N ± 2/3/4/5 has a minimum NTSC to NTSC spacing of 20 miles because of intermod interference.

N ± 7 has a minimum spacing of 60 miles because of if beat and local oscillation radiation.

N ± 8 has a minimum spacing of 20 miles because of if beat interference.

N ± 14 has a minimum spacing of 60 miles because of interference between the visual and aural carrier.

N ± 15 has a minimum spacing of 75 miles because of interference between the visual and aural carrier.

DTV interference into NTSC has a much simpler set of rules:

Channel −2 = −24 dB desired-to-undesired ratio
+2 = −28
−3 = −30
+3 = −34
−4 = −34
+4 = −25
−7 = −35
+7 = −43
−8 = −32
+8 = −43
+14 = −33
+15 = −31

To ensure that DTV does not interfere with NTSC, the FCC has prescribed an extremely sharp bandpass filter or channel mask: ± 2.5 MHz = −35 dB, and −110 dB at the far side of an adjacent channel.

In some areas channels 16 and 17 are shared with land mobile. A few other channels may have adjacencies as well such as with radio astronomy. Adjacent DTV stations may have special out-of-channel emission limits imposed.

Many stations have DTV channel assignments adjacent to their existing NTSC assignment. The channel above the current NTSC channel is known as $N + 1$ and an adjacent assignment below is known as $N - 1$. An $N + 1$ channel assignment is more problematic because the DTV signal provides interference with the NTSC's aural carrier. The DTV pilot and the NTSC aural carrier are fairly close together. The filter transition region for $N + 1$ between the upper sidebands of the NTSC aural carrier and DTV energy is approximately 460 kHz apart. For $N - 1$ there is approximately 800 kHz of separation.

13.1.2 The modulation debate

The "which modulation approach is best" argument is another issue that plagues the initial DTV roll-out. Many are still lobbying for the ATSC or FCC to scrap the 8-VSB system. The 8-VSB road has been traveled too far already to return to the start, though. However, we will look briefly at the major contender and why many like it. Lately, some have advocated allowing more than one modulation scheme to be used.

Coded orthogonal frequency division multiplexing, or COFDM, is sort of a parallel path between the transmitter and receiver, as opposed to the usual serial path of most transmissions. European, Japanese, and Australian systems use OFDM. This parallel approach is accomplished by dividing transmitted data among hundreds of narrowband low-speed carriers located side by side, instead of the single wideband carrier normally used. The frequency division multiplexing part of COFDM alludes to the use of many carriers. The "C" in the acronym stands for coded, which means forward error correction is added. The use of many carriers means that the individual symbol time of each carrier can be fairly long, which minimizes multipath interference. The carriers overlap one another, but since they are orthogonal, that is, perpendicular, or quadrature to adjacent carriers, the product of two adjacent carriers integrates over a symbol period to equal zero.

However, OFDM is more computationally intensive than 8-VSB. It uses thousands of quadrature-modulated carriers to transmit large quantities of data at a low symbol rate. A major factor in the ATSC's choice of 8-VSB was the need to keep DTV signals from interferring with NTSC signals.

13.1.3 8-VSB modulation

Two flavors of VSB are available. The first is 16-VSB, which is intended for use by cable systems. It is less robust against white noise than the terrestrial 8-VSB version. One segment error per second exists when the 8-VSB S/N ratio approaches 15 dB. If 16-VSB is used, the S/N ratio must be about 28 dB for the same error rate. For comparison, an NTSC signal is considered to have marginal quality with a S/N ratio of 34 dB, which means that an 8-VSB signal has 19 dB more S/N ratio headroom before it is no longer viewable. As a result, assigned DTV power levels are generally 12 dB less than their NTSC counterpart. This still allows DTV a 7-dB margin over NTSC.

An 8-VSB transmitter consists of 10 blocks. The first four are data processing blocks and final six are for signal processing. The first block is known as the "data randomizer," and this block enables the 8-VSB modulation process to produce a flat spectrum across the channel. This also minimizes DTV interference into NTSC receivers by making the DTV receiver signal appear as white noise. It only randomizes MPEG data. Parity bytes, data field sync, and data segment sync are added later.

The next block is the Reed-Solomon encoder. Twenty Reed-Solomon parity bytes are added to the end of each 187-byte MPEG data packet (the single byte of data sync at the start of each MPEG-2 data packet is not coded), which has been randomized. The result is 207-byte packets. This scheme can correct up to 10 byte errors per packet.

The next block is the trellis encoder. This forward error corrector adds 1 FEC bit for every 2 data bits. Therefore, each ATSC symbol carries two randomized MPEG packet, or Reed-Solomon bits, and 1 FEC bit.

Next comes the multiplexer. This block adds segment and frame sync. Segment sync has no FEC bit added. Since it is 1 byte long, it can easily be encoded across four symbols. Segment sync occurs every segment. Counting the four symbols used as segment sync, each segment consists of 336 symbols. Thus

$$207 \text{ bytes/segment} \times 8 \text{ bits/byte} = 1656 \text{ bits/packet}$$

$$1656 \text{ packet bits} + 828 \text{ FEC bits} = 2484 \text{ packet and FEC bits/segment}$$

$$\frac{2484 \text{ bits/s}}{3 \text{ bits/symbol}} = 828 \text{ symbols/packet}$$

$$\begin{aligned} 828 \text{ symbols/packet} + 4 \text{ segment sync symbols} \\ = 832 \text{ symbols/segment} \end{aligned}$$

A frame sync is inserted every 313 segments. Frame sync is 832 symbols long. The first four symbols are for sync, and the 511 symbols are a pseudorandom sequence of data to produce a flat spectrum that is analyzed by the receiver. These symbols are used to determine linear distortion in the signal, which the receiver then corrects for. Next, a pseudorandom sequence of 63 symbols is sent three times. The middle 63-bit sequence is inverted every other frame sync. Twenty-four symbols indicate which VSB mode is present. Although the ITU has five modes (2-/4-/8-/16-VSB or 8T-VSB), ATSC only has two modes (8-/16-VSB). Mode 8-VSB is the terrestrial broadcast mode, while 16-VSB is intended for cable transmission. It should be stressed that ATSC timing bears no reference to NTSC. Each segment is 77.3 μs long, and frame sync occurs every 24.2 ms, resulting in a frame rate of 41.322.

The digital VSB transmission system uses three supplementary signals for synchronization:

A low-level pilot is employed for carrier acquisition.

A data-segment sync is employed for synchronizing the data clock in both frequency and phase.

A data-frame sync is employed for data framing and equalizer training.

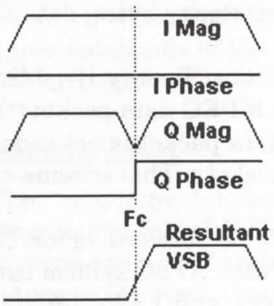

Figure 13.1 Hilbert transform.

This is far more robust than a regular data modem that uses the data signal alone to achieve synchronization. A regular modem will lose all synchronization if the received signal drops below the received threshold (Fig. 13.1). The 8-VSB modulation scheme is a quadrature-modulated system, with I and Q components just like NTSC's color subcarrier. Like the color system, a baseband I and an orthogonal Q modulate a carrier. However, the purposes of the two ATSC components are radically different than their NTSC color equivalents. The I actually conveys the ATSC data values by assuming one of eight values of magnitude (Fig. 13.6) along the I axis. The Q signal is used to minimize bandwidth by canceling the lower rf sideband. The Q channel has a fixed relationship to the I channel and can be described as a pseudo–Hilbert transform. The Hilbert transform has lower sideband power with a phase relationship 180° apart from upper sideband power. The Q channel is constructed so that it has no dc component. Since the Q channel's lower sideband has a phase opposite that of I, most of the lower sideband is eliminated when I and Q are combined (see Fig. 13.1). In a perfect DTV rf system, at the midpoint of the symbol period, the I signal value will be one of eight data amplitude levels. Any linear or nonlinear distortion in the transmission process will cause the I signal amplitude at the center of the symbol time to be incorrect. The Q signal lacks the discrete levels that the I has and contains no digital data information for the receiver. Each I symbol value can be thought of as an impulse, which causes considerable pre/postringing. However, the ringing passes through 0 at preceding and succeeding symbol sample times. Therefore, this ringing does not add to other I samples (that is, no intersymbol interference). The final 8-VSB signal bears no resemblance to the I signal vector that created it. The extent to which the actual I component sample point departs from the ideal sample point is called the *error vector magnitude* (EVM; Fig. 13.3). The difference between one of eight I values along the I axis (-100 to $+100$ percent) is 28.6 percent (200/seven spaces between I values). Therefore, when the EVM value exceeds one-half of 28.6 percent (14.3 percent), slicing errors will result.

A simplified method of developing 8-VSB modulation follows. Start with QAM (I and Q), cut the Q data rate in half, double the I data rate, cut one sideband to create a single sideband, and then suppress the carrier. The result is amplitude components, without reliance on phase components.

The pilot signal in the ATSC channel is a continuous wave (CW) signal, while the rest of the spectrum is uniformly filled with noiselike information. The low-level rf pilot is a constant rf level, and adds only 0.3 dB to the total signal power (although the voltage level of the pilot is 3 dB above average power). However, this low-level pilot aids carrier recovery independent of data. This provides reliable carrier recovery down to S/N ratios of 0 dB, well below the data-error threshold, which is $\geq$10 dB. The low-level pilot is created by adding a dc value to the baseband data, which have a zero mean because all data levels are equally probable. It should be noted that the apparent level of the CW pilot signal with respect to the rest of the noiselike data signal is a function of the spectrum analyzer's resolution bandwidth filter setting. To check the DTV signal, the analyzer's resolution bandwidth should be set to 30 kHz and heavily averaged.

Some exciters use DSP filters with many taps; one uses 72, for EVM precorrection. The tap coefficients are derived using an HP89441A vector signal analyzer (VSA) to determine the values required. These are then loaded into the exciter from the VSA. Power out of the exciter is usually around 5W, but some are capable of as much as 250 W out (Figs. 13.2 and 13.3). EVM is a parameter that many seem to pay attention to. However, it turns out that the channel signal-to-noise ratio is a direct indication of EVM. In the testing protocol used by the Model Station Group for early reception testing, S/N ratio was used instead of EVM. It's interesting to note that the eyes can be completely closed, with no errors occurring in the receiver due to the heavy error correction employed. Errors start to occur when EVM approaches 15 percent. Vectors at the corners of the I/Q quadrant represent maximum power (Figs. 13.3 and 13.4). Any group delay in the system will skew the dots off the vertical access. EVM of 2.3 to 3 percent out of an exciter is equal to approximately a 31-dB S/N ratio. This is generally the best specification claimed. An EVM of 4 percent equates to an S/N ratio of 28 dB. An exciter output with 2.4 percent EVM has an S/N ratio of 31 dB. Thus

$$\text{S/N ratio} = 20 \log \frac{1}{\text{EVM}}$$

The DTV transmitter total power out (TPO) rating is a peak value because the rf peak envelope excursion must transverse the linear operating range of the transmitter on a peak basis to avoid high levels of IMD spectral spreading. The DTV peak envelope power (PEP) is similar to the NTSC peak of sync rating for setting the transmitter power level by noting that the NTSC linearizes the PEP envelope from sync tip to zero carrier for best performance. ATSC has no peak power, but its average power is very stable. Typically, 99.9 percent of the transmitted digital VSB signal peaks are within 6.3 dB of its average power. Vectors at the corners of the I/Q quadrant represent maximum power (Fig. 13.4).

While many UHF transmitters use a pulsed system where the major portion of envelope linearization only extends from black level to maximum white, the DTV signal has no repetitive peak to apply a pulsing system. DTV power is always stated as average (rms) because this is the only consistent parameter of an otherwise pseudorandom signal. Four times average power occurs about

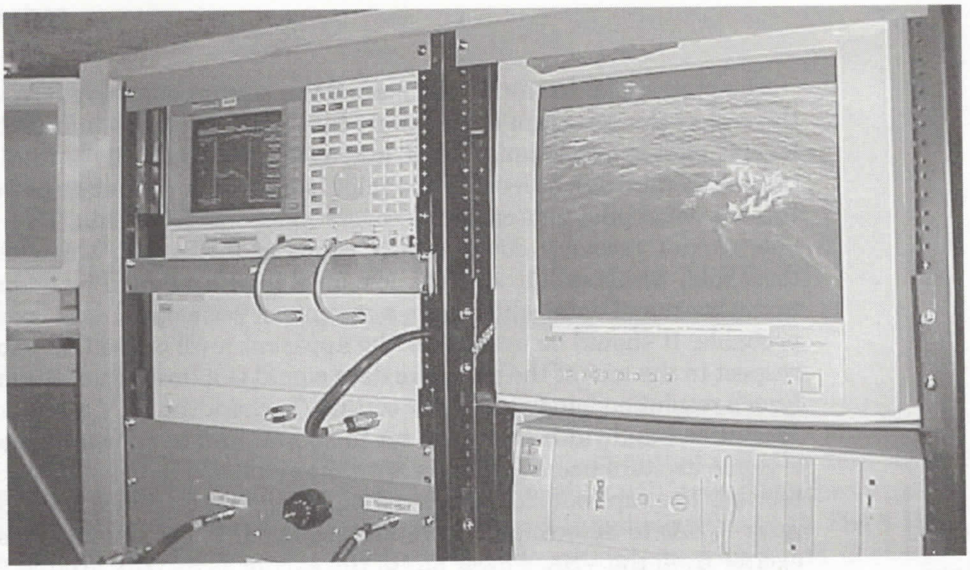

Figure 13.2 VSA (left rack) installed in an ATSC reception test vehicle. Notice DTV display on PC monitor (RGB) in the right rack.

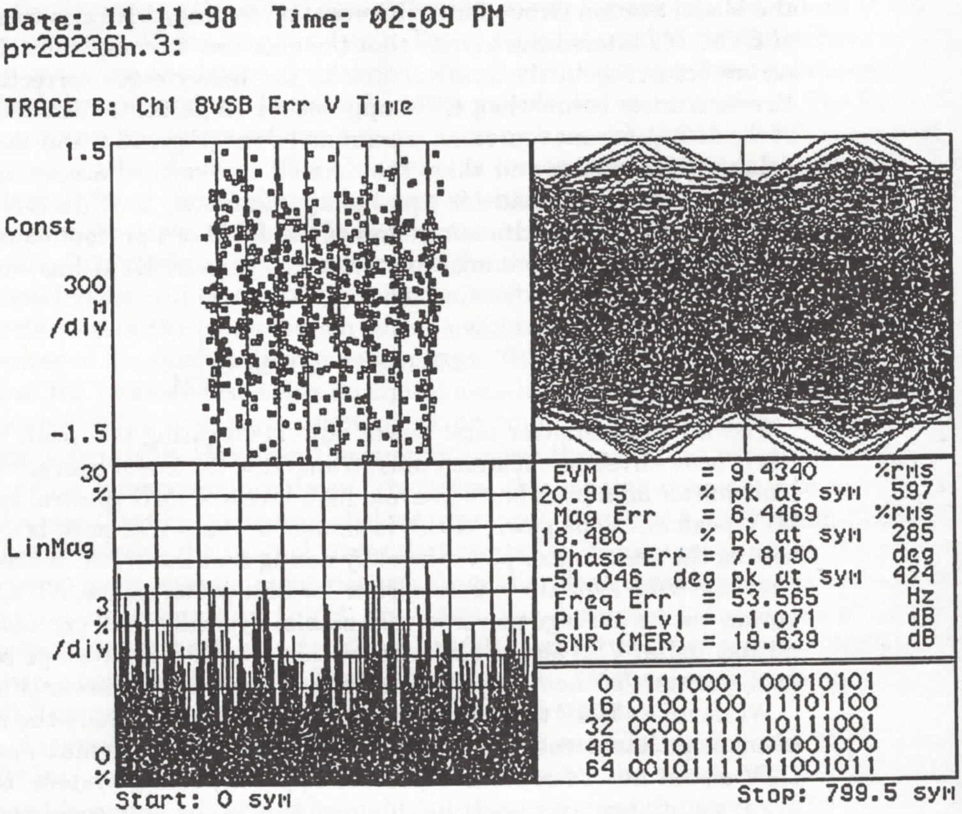

Figure 13.3 8-VSB constellation and eye pattern display from VSA.

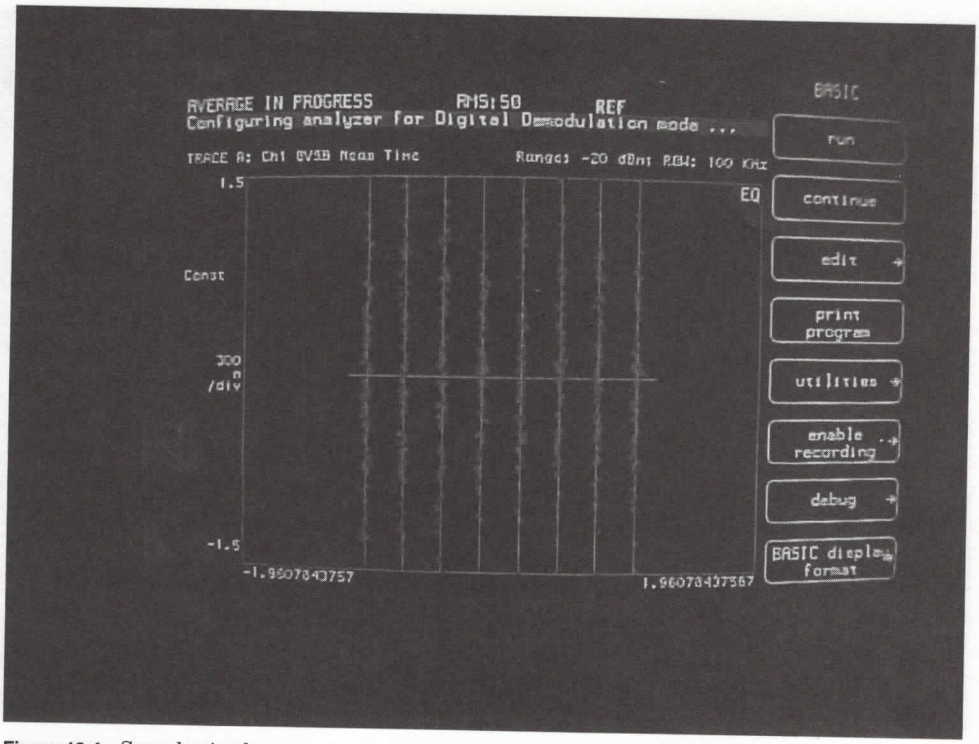

Figure 13.4 Samples in the corners require more power than samples near the center.

2 to 3 percent of the time, and 6 to 6.3 dB above average occurs about 0.1 percent of the time (Fig. 13.5).

It is usually under continuous wave that an antenna's radiation pattern and gain are defined. NTSC is considered to be narrow enough to essentially be considered CW, but DTV occupies the entire band and is considered wideband. DTV occupies the middle 5.38 MHz of its 6-MHz space. NTSC channel energy consists of three carriers—visual, chroma, and aural. The signal energy rapidly falls away from these carriers. NTSC maximum power is generally 2 MHz above the visual carrier. However, the DTV spectrum is flat across the whole 6-MHz channel, except for the last 0.3 MHz. The effective NTSC bandwidth is less than 4 MHz, but the entire DTV channel is of equal importance.

There is nothing digital about the transmission of a DTV rf signal. The channel, like NTSC, is 6 MHz wide. But the entire channel is occupied with energy. The DTV rf signal is essentially a single-sideband suppressed-carrier transmission. DTV transmission has better bandwidth and power efficiency than AM. With 100 percent AM sinusoidal modulation the overall power increases to 150 percent, with 100 percent still in the carrier and 25 percent in each of the upper and lower sidebands. With 8-VSB, all the available transmit power is used to convey the information contained in only the upper sideband. There is a pilot 0.31 MHz for the lower end of the channel.

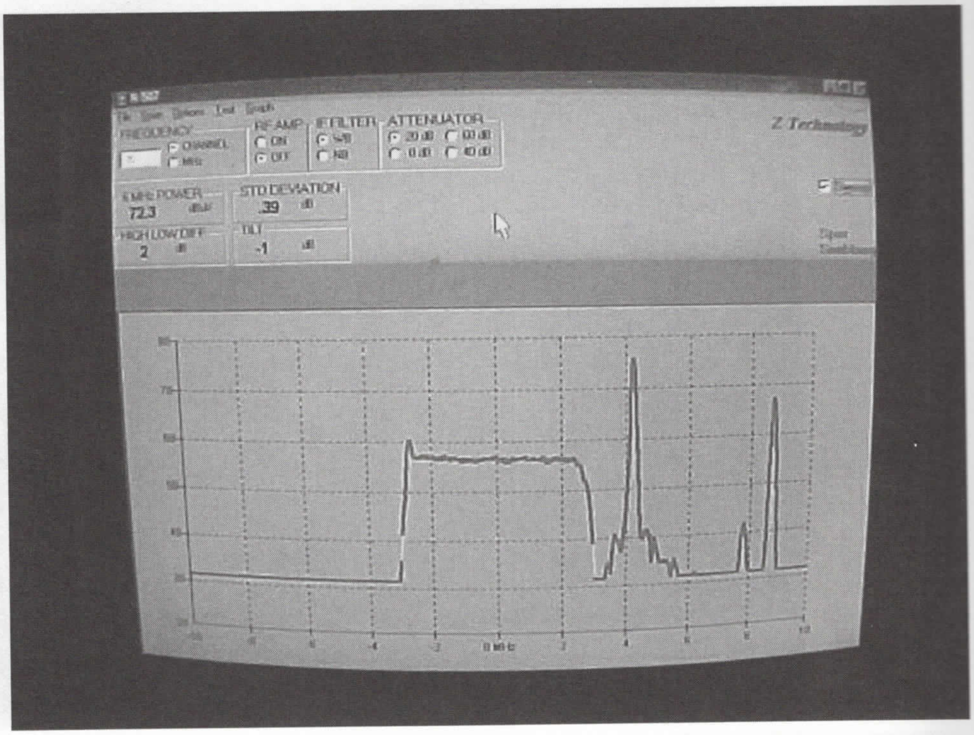

Figure 13.5 DTV signal adjacent to NTSC signal.

The 8-VSB signal has eight possible levels in the *I* component: +7, +5, +3, +1, –1, –3, –5, and –7 (Fig. 13.6). At eight levels, it means each symbol carries 3 bits. The symbol rate for the ATSC channel is 10,762,238, which is exactly double the 5,381,119-MHz, 3-dB bandwidth for the DTV channel. The symbols are exactly double the channel bandwidth because two symbols butted together, each with a different value, can be thought of as one complete cycle of a waveform. That waveform would have a fundamental frequency based on the whole waveform period, which is 2 times the period (or one-half the frequency) of each symbol. At 3 bits/ symbol, this means that the DTV channel carries 32.28 Mbits/s of data. However, more than one-third of this data is used for data synchronization and FEC. The actual data payload is 19.28 Mbits/s.

13.1.4 Channel management

DTV does not mean that your analog skills will go away. You must stay cognizant of the fact that processing does not end at your ATSC transmitter's encoder. A lot of what makes ATSC so robust is the high-powered VSB signal processing that takes place in the consumer's receiver, whether an out-and-out television or just a set-top box.

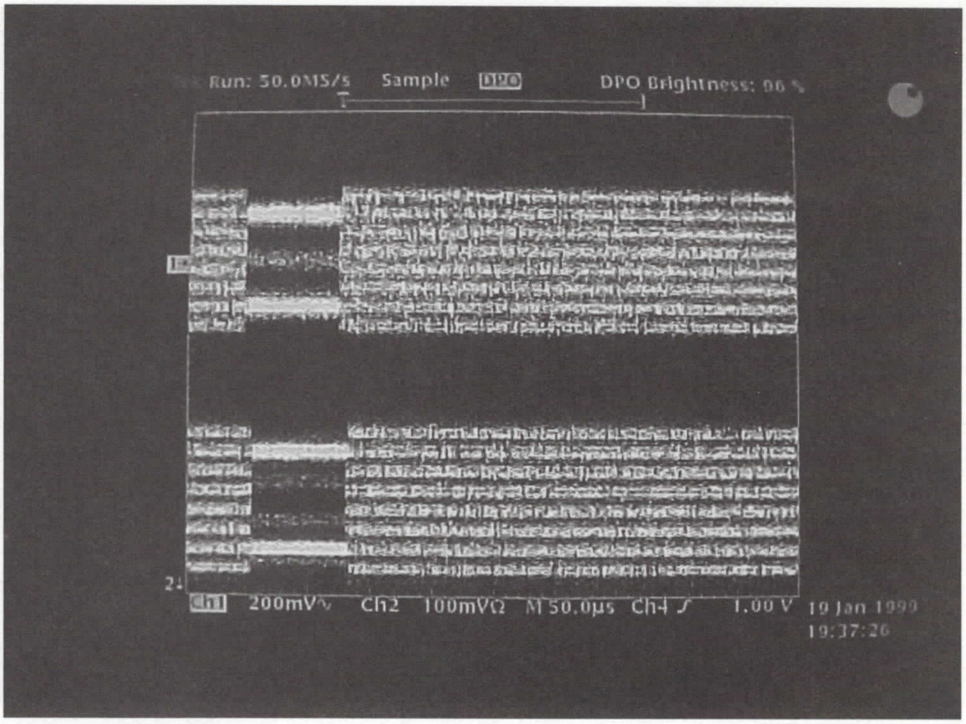

Figure 13.6 An *I* signal can assume one of eight values. This component carries the information content of the 8-VSB signal. The top signal is before processing; the bottom is after.

Once again, it is being driven home to us that just as analog audio and video will be around, your analog skills need to stay intact as well. Noise used to be the limiting factor in terms of how far out a signal could be viewed. With ATSC, it is not only noise but also transmit linearity. As nonlinearity gets worse, out-of-band performance gets worse (remember the FCC channel mask) and the in-band signal-to-noise ratio gets worse. Passband amplitude distortion and group delay affect the S/N ratio.

Although transmitter manufacturers are playing "specmenship" when it comes to S/N ratios out of their boxes, Zenith claims that 27 dB is sufficient. Some manufacturers claim values well into the 30-dB range. One has to wonder if this is necessary or just desirable. At 33 dB, the 8-VSB noise threshold is 15.1 dB. At 27 dB, it is 15.25 dB, which is a worst-case scenario if all the noise is uncorrelated. To keep this value as high as possible, all the analog specs remain important. Also, the signal-to-noise ratio relates directly to EVM. This is the value often reported as an indication of 8-VSB's health. Again, manufacturers' "specmenship" has values between 2 and 5 percent. Those values can be seen out of the transmitter but not at most receive sites. Values approaching 15 percent can be seen as the error cliff is approached. Linearity is extremely important. The coverage area will shrink as the system becomes nonlinear. Group delay will start to rotate the *I*/*Q* 8-VSB constellation.

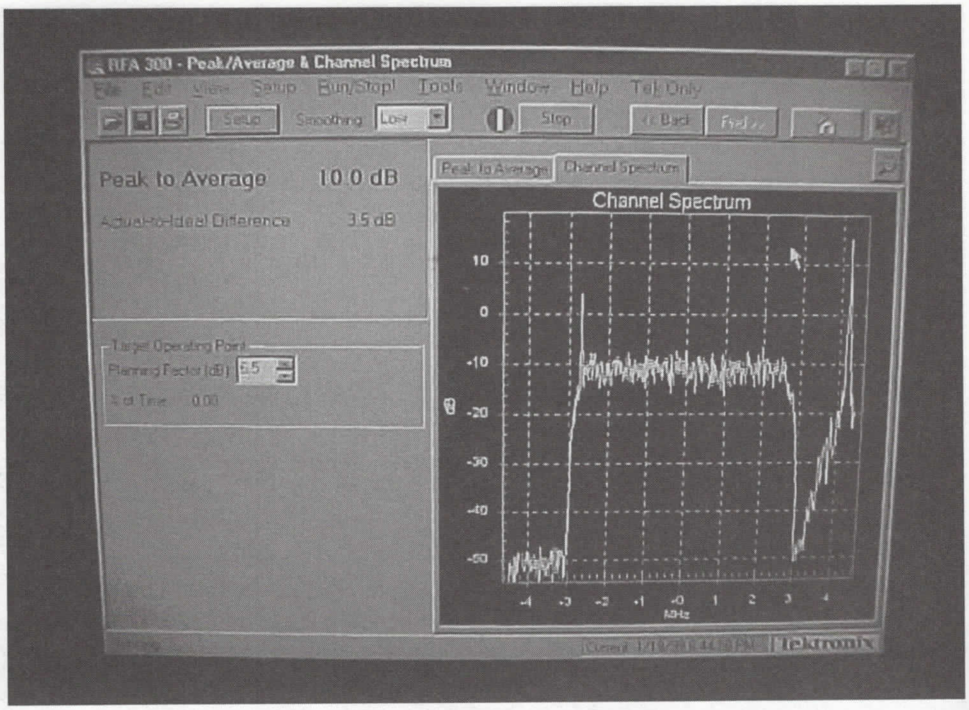

Figure 13.7 DTV channel spectrum. The spike at the lower (left) end of the channel is the pilot signal.

Intermodulation distortion in the rf amp of the DTV transmitter will produce emissions in adjacent channels. Any nonlinear amp will produce IMOD products. The shoulders at either end of the channel rise because of intermod. Each amplifier in the rf chain not only amplifies the band of frequencies in but also harmonic images of the original signal. The second harmonic band will be twice as wide as the original. The output of the second amp would create an 18-MHz image under the desired 6-MHz-wide signal because of additional heterodyning between the undesired image and the desired signal. Low-pass filtering can minimize the upper sideband images, but the lower sideband images are hard to eliminate (Fig. 13.7).

All DTV devices are run class AB. Devices are more efficient as they are driven harder because the signal approaches the power supply rails so there is less wasted power in the amp. Also, more signal drive means more power variation. Only deltas in power can be coupled out of the final.

13.1.5 Channel conversion

Most DTV stations will face the decision on which channel to continue transmission on at the end of the DTV transition. For those stations that are assigned out-of-band channels (>51) there will be no choice; they will have to go back to the in-band channel that was previously occupied by their NTSC channel. For many UHFs that moved to UHF the decision will probably solely rely on economic issues as to whether they should stay on the new channel or move back. But for VHFs that have new UHF assignments, and the few UHFs that find themselves in the VHF band, there will be issues other than the economics of maintaining a transmitter.

It is suspected that many VHF NTSCs with UHF DTVs will opt to go back to VHF when the transition is over. Why not? Coverage is easier and transmitters are generally tamer beasts that use less space and power. But does it actually make economic sense? Let's look at the engineering needed to convert a transmitter from one channel to another. The channel conversion for an IOT transmitter is

Exciter. Retune or swap the output filter. Generally, there are three different filters to cover the UHF band and one for VHF. Regardless of the filter required, new channels can usually be selected with dip switches.

IPA. Replace circulators. There are four different circulators that cover the UHF band. Adjust the feed-forward delay lines.

HPA. Change the cavity. The UHF band has two different cavities based on whether you are at the high or low half of the UHF band. The IOT will also need to be retuned and metering will have to be recalibrated.

RF. Magic tee and channel masking filter will have to be replaced. The total conversion cost for the IOT transmitter could be above $400,000.

The channel conversion for a solid-state transmitter is as follows. Amplifier modules are each wideband enough to cover one-fourth of the UHF band. If the channel being moved to is in a different UHF quadrant, the modules will have to be replaced. Modules represent about 80 percent of the total transmitter cost. Today, they cost around $800 each. As in the IOT box, circulators will have to be replaced if the new channel is in a different quadrant than the old channel. Combiners and dividers will be replaced or retuned. Additionally, the same exciter and rf plumbing requirements exist in the solid-state unit as in the IOT unit. Total conversion costs for a solid-state transmitter could be over $500,000.

13.2 Television Transmitters

There are approximately nine transmitter vendors selling in the United States. Power ranges from 200 W to 300 kW. Where an average 20- to 40-kW VHF transmitter would cost approximately $2700/month to operate, the average UHF transmitter can cost over $10,000/month in operation costs. Most VHF stations can afford full redundancy in their transmitters, but full backup for UHF is costly. UHF transmitters can require 30 to 50 tons of air conditioning. (*Note:* 1 ton of air conditioning can handle approximately 4 kW; 12,000 Btu = 1 ton of air conditioning = 3516.85 W.) A typical tube DTV transmitter