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LINEAR DISTORTIONS, PART 1

By RON HRANAC

One way to increase a cable network's high-speed data and voice service throughput is to use higher orders of modulation. For instance, switching from quadrature phase shift keying (QPSK) to 16-QAM (quadrature amplitude modulation) will double the data rate in the same upstream RF channel bandwidth. Data rates vs. modulation types and channel bandwidths supported by Data Over Cable Service Interface Specification (DOCSIS) and Euro-DOCSIS 1.x are summarized in Tables 1 and 2.

Table 1: DOCSIS and EuroDOCSIS downstream data rates

Table 2: DOCSIS and EuroDOCSIS 1.x upstream data rates

But higher orders of modulation and sometimes also wider channel bandwidths are more sensitive to cable network impairments, especially those that can't be seen on signal level meters (SLMs) or conventional spectrum analyzers. Some of the more common so-called invisible impairments - which actually are linear distortions - include micro-reflections, amplitude ripple and tilt (poor frequency response), and group delay.

Ever wonder why that clean upstream with 30+ dB carrier-to-noise ratio (C/N), with no visible ingress or other impairments in the vicinity of the data carrier, won't support 16-QAM, yet QPSK works fine? How about the challenges faced when changing downstream digitally modulated signals from 64-QAM to 256-QAM? The problem may very well be linear distortions.

What are linear distortions? They are impairments that occur when a signal is subjected to channel characteristics such as poor frequency response, bent-line phase response or both. One way to tell if an impairment is a linear distortion is to change the amplitude of the desired signal. If the impairment's amplitude relative to the desired signal stays the same, it's probably a linear distortion. Linear distortions can seriously impair data signals carried on cable networks.

This article provides an overview of linear distortions and the impact they have on high-speed data transmission; describes the causes of linear distortions and how to prevent them; and offers practical troubleshooting tips and useful references for when they do occur. Examples from real-world cable systems show what linear distortions look like on the specialized test equipment required to see them and how the same spectrum appears to be unimpaired when viewed on a conventional spectrum analyzer display.

An understanding of linear distortions is critical to achieving the reliability necessary for new services being deployed on today's cable networks. Video, data and voice are converging in cable network designs. To ensure smooth transitions in this convergence, cable operators must develop and implement test methodologies that account for linear distortions in their networks.

A clean upstream: or is it?

Figure 1 shows the upstream spectrum at the output of a cable network's headend optical receiver. The spectrum analyzer's span control is set to 100 MHz, which allows displaying both the 5-42 MHz upstream and any clipping distortion that may be present between 42 and 100 MHz. The analyzer's vertical scale is 10 dB/division. An upstream 3.2 MHz bandwidth test signal's center frequency is 32.75 MHz, well below the diplex filter roll-off area. The upstream C/N is a bit better than 35 dB, and ingress is quite low. There was no evidence of common path distortion (CPD) or impulse noise. Yet on this apparently clean upstream, 16-QAM would not work!

Figure 1: Upstream spectrum display to 100 MHz

The culprit? Linear distortions, which cause inter-symbol interference and degrade the data signal's modulation error ratio (MER). Linear distortions generally cannot be seen on conventional spectrum analyzers and SLMs. So how does one go about determining whether linear distortions exist, then troubleshoot and fix them when they do occur?

Micro-reflections

One class of linear distortions is micro-reflections, which are caused by impedance mismatches. Micro-reflections are a common problem in cable networks and usually affect upstream signals more than downstream signals. This is because coaxial cable's greater attenuation at downstream frequencies tends to dampen the impedance mismatch-related reflections more. Before looking at micro-reflections in more detail, it's useful to review what happens in the world of RF transmission when impedance mismatches exist.

In the ideal world of transmission line theory, the signal source, transmission medium and load have equal impedances (Z). All power transmitted by the source - the incident power - is absorbed by the load, as shown in Figure 2. The transmission medium is assumed to be lossless in this example.

Figure 2: Ideal transmission line example

In the real world, the impedances are rarely, if ever, exactly equal. When an impedance mismatch exists in the transmission medium or at the load, some of the incident signal's power is reflected back toward the source. (See Figure 3.)

Figure 3: Impedance mismatch at the load

When the first reflection - or echo - reaches the source, some of it is reflected by the source, causing a second echo. The second echo travels back down the line toward the load. It arrives at the load at a slightly later time than the incident signal. This is illustrated in Figure 4.

Figure 4: Impedance mismatch at the source

In the example shown in Figure 5, a signal source is connected to a load via a transmission medium - say, coaxial cable. The source and load are each assumed to have 7 dB return loss, and there is 1 dB of attenuation in the transmission medium connecting the source and load.

Figure 5: Transmission line example with 7 dB return loss impedance mismatches at source and load

In Figure 6, a +31 dBmV signal leaves the source at time T0. The signal is attenuated 1 dB before reaching the load at time T1, making the signal amplitude +30 dBmV. The load's poor return loss (7 dB) causes a reflection (echo) whose amplitude is +23 dBmV (+30 dBmV incident signal amplitude - 7 dB RL = +23 dBmV echo amplitude). This first echo travels back toward the source and is attenuated 1 dB to +22 dBmV. The poor return loss of the source (also 7 dB) causes a reflection from the source back toward the load, at an amplitude of +15 dBmV. The second echo travels from the source to the load and reaches the load at time T2 with an amplitude of +14 dBmV, or -16 dBc relative to the original signal at the load. That is, the original - or incident - signal at the load has an amplitude of +30 dBmV, and an echo whose amplitude is +14 dBmV (-16 dBc) also is present at the load. The echo is delayed relative to the incident signal by the amount of time it took for the first echo to travel from the load to the source, be reflected by the source, and travel back to the load. This time delay is equal to T2 - T1.

Figure 6: Incident signal and echo relationships

In the real world, a comparable example might be two taps separated by 100 feet of half-inch coaxial cable. Assume that both taps are water-filled, causing impedance mismatches that reduce the taps' normal return loss of 15-19 dB to only 7 dB. The 100-foot span of cable is assumed to have 1 dB of attenuation.

Electromagnetic signals travel through hardline 75 ohm coaxial cable (87 percent velocity of propagation) in about 1.17 nanoseconds (ns) per foot. It takes about 234 ns for the echo to make the round trip from the load to the source and back to the load again in a 100-foot span of hardline cable. The +14 dBmV echo at the load is delayed 234 ns relative to the +30 dBmV incident signal and is 16 dB lower in amplitude than the incident signal. This relationship is represented graphically in Figure 7. The height of the larger vertical line is the incident signal's amplitude in dBmV. Its horizontal position in the figure is an arbitrary time T1 that the signal arrives at the load. The reflection (echo) is shown as the smaller vertical line at time T2, the slightly later time that it arrives at the load. Here the incident signal is +30 dBmV, and the echo - delayed by time T2 - T1 (234 ns) - is +14 dBmV, or 16 dB below the amplitude of the incident signal.

Figure 7: Incident signal and echo in the time domain

In the frequency domain, the echo interacts with the incident signal to produce a standing wave, which shows up on broadband sweep equipment as a standing wave - that is, amplitude ripple - in the displayed frequency response. An example is illustrated in Figure 8.

Figure 8: Amplitude ripple in the frequency domain

One can calculate the amplitude of a single echo relative to the incident signal from the frequency domain display as follows. Assume the standing wave's peak (VP) = +31.28 dBmV (36.63 mV) and the null (VN) = +28.5 dBmV (26.61 mV).

Echo = 20log[(VP - VN)/(VP + VN)]
Echo = 20log[(36.63 - 26.61)/(36.63 + 26.61)]
Echo = 20log[10.02 / 63.24]
Echo = 20log[0.16]
Echo = 20[-0.80]
Echo = -16 dBc

Use the formula D = 492 x VP/F to calculate the approximate distance to an impedance mismatch. D is the distance in feet to the fault from the test point; VP is the cable's velocity of propagation (typically ~0.87 for hardline cable); and F is the frequency delta in MHz between successive standing wave peaks on the frequency domain sweep display. The amplitude ripple peaks in Figure 8 are about 4.27 MHz apart, so the distance to the fault is:

D = 492 x VP/F

D = 492 x 0.87/4.27
D = 492 x 0.2037
D = 100.27 feet

The effects of impedance mismatches on analog TV channels can, if serious enough, cause a familiar impairment. In an analog TV channel, an echo caused by an impedance mismatch may result in visible ghosting in the TV picture. A second image - offset in time and amplitude - appears to the right of the incident signal. This is shown in Figure 9.

Figure 9: "Ghosting" in an analog TV picture

What would "ghosting" look like in a time domain display of baseband digital data? It might appear as shown in Figure 10 - a "ghost" image of the original data, offset in time and amplitude. (In reality, the echo and incident signal will add, distorting the actual waveform.) If the reflection were severe enough, the data receiver might not be able to differentiate the original data from the ghost data, resulting in errors. The bigger problem, though, is amplitude ripple and possibly also group delay ripple. These cause inter-symbol interference, which degrades the data signal.

Figure 10: "Ghosting" in a baseband data signal

Some of the more common causes of micro-reflections include:

- Damaged or missing end-of-line terminators
- Damaged or missing chassis terminators on directional coupler, splitter or multiple-output amplifier unused ports
- Loose center conductor seizure screws
- Unused tap ports not terminated; this is especially critical on low-value taps
- Poor isolation in splitters, taps and directional couplers
- Unused drop passive ports not terminated
- Use of so-called self-terminating taps at feeder ends-of-line
- Kinked or damaged cable (includes cracked cable, which causes a reflection and ingress)
- Defective or damaged actives or passives (water-damaged, water-filled, cold solder joint, corrosion, loose circuit board screws, etc.)
- Cable-ready TV sets and VCRs connected directly to the drop (return loss on most cable-ready devices is poor)
- Traps and filters with poor return loss in the upstream (common with some filters used for cable modem-only service)

Amplitude ripple and tilt

Amplitude ripple and tilt are more commonly known in cable industry vernacular as frequency response, although to be technically correct, it should be called amplitude-vs.-frequency response, or magnitude-vs.-frequency response. True frequency response is a complex entity, containing both magnitude and phase components. Cable TV broadband sweep gear is used to display the amplitude (magnitude) component of frequency response, but is incapable of displaying the phase component. As such, sweep equipment can be useful for troubleshooting amplitude ripple and tilt, but not group delay.

Figure 11 includes two screen shots from cable TV broadband sweep equipment. On the left, an Acterna SDA5000 display shows amplitude tilt, where the amplitude response changes more or less steadily with frequency between 54 MHz and 750 MHz. This is most likely a result of improper network alignment. In the screen shot on the right, amplitude ripple is evident on the Calan (Sunrise Telecom) 3010 sweep receiver display, as is amplitude tilt. Note that the amplitude response tilts one direction in the lower part of the 5-35

MHz spectrum and another direction in the upper part of the spectrum. This indicates a combination of at least one micro-reflection caused by an impedance mismatch, as well as network alignment problems.

Figure 11: Broadband sweep examples of amplitude tilt and ripple

To troubleshoot amplitude ripple and tilt with forward and reverse sweep equipment, use the maximum supported resolution to more easily see closely spaced amplitude ripple. Cisco Systems' John Downey offers these tips when troubleshooting reflection-related sweep response problems:

- Resistive test points facilitate efficient troubleshooting because they more readily display standing waves in the sweep response.
- Use the previously mentioned formula D = 492 x VP/F to calculate the approximate distance to an impedance mismatch.
- Specialized test probes from Corning-Gilbert (NS-9178-1) and Signal Vision (SV03) are better than using conventional housing-to-F adapters when using passive or active device 5/8-24 port seizure screws as test points.
- When troubleshooting micro-reflections with sweep equipment, reverse sweep is usually better than forward sweep because sweeping at lower frequencies can give more accurate distance and resolution. Assuming a sweep point every 1 MHz, the tightest that observed "ringing" (standing wave delta) could be is 2 MHz, leading to a distance resolution of 492 x .87/2 = 214 feet. An impedance mismatch this far away from the test point wouldn't appear very pronounced on a forward sweep because of the greater downstream coaxial cable attenuation and the typical forward sweep point resolution of only 6 MHz.

The goal is to achieve frequency response that is as flat as possible over both the forward and reverse operating spectrums.

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