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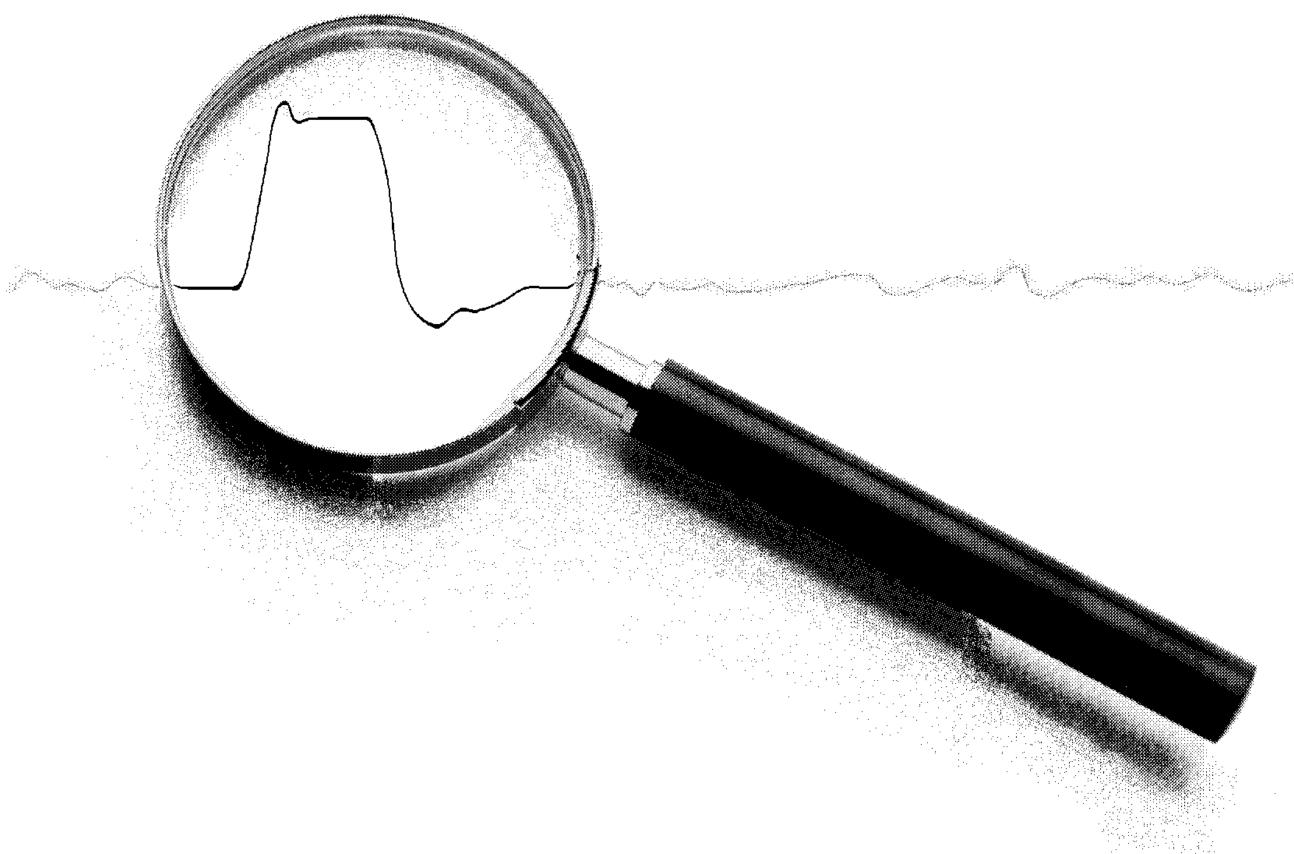
AN7

Application Note

Measurement and Evaluation of Pulse Shapes in T1/E1 Transmission Systems

By Roger Taylor



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Introduction

The T1 (1.544 Mbps) transmission system is widely used in North American public and private telephone networks. An analogous system, PCM-30 (2.048 Mbps), is used outside North America. Both of these primary rate transmission systems must meet exacting pulse shapes as described in Bellcore TR-NWT-000499, ANSI T1.102-1993, AT&T CB-119 and CCITT G.703. Crystal Semiconductor T1 and PCM-30 line interface devices have pulse shaping line drivers whose output pulses are designed to meet the pulse-shape requirements of the specifications stated above. Measuring these pulses to ensure they comply with the specifications is not as straightforward as it may seem. This paper covers pulse shape measurement techniques to allow accurate assessment of T1 and PCM-30 pulse shapes.

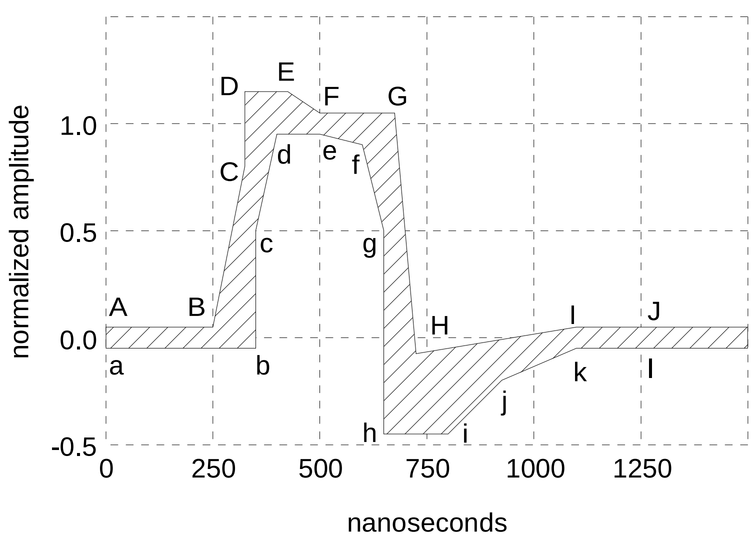
Pulse Shape Requirements

T1 equipment designed for central office use must interface with a DSX-1 cross connect. For most applications, the transmitter is located within 655 feet of the cross connect. All T1 pulses arriving at the cross connect must meet the pulse amplitude and template requirements at the cross connect as shown in Figure 1, whether the originating transmitter is a few feet away or 655 feet away. The line is terminated with a 100 Ω load. The pulse amplitude is measured at the center of the pulse and must be within 20% of 3.0 volts according to CB-119. (Other specs differ slightly; be sure to consult the applicable spec.) If the amplitude requirement is met, the pulse may be linearly scaled to fit within the template.

PCM-30 pulse shapes are specified in Rec. G.703. In this case, the pulses are measured at the output of the line driver only, and *not* required to meet the pulse template over a variety of cable lengths. The pulse must fit the template without scaling.

For 2.048 MHz operation, there are two amplitudes specified depending on the type of cable used. For 75 Ω coax, the pulse height is 2.37 volts ±10%. For 120 Ω symmetrical (shielded-twisted) pair, the specified pulse amplitude is 3.0 volts ±10%. The CCITT G.703 template for 2.048 MHz operation is shown in Figure 2.

CCITT also specifies a template for operation at 1.544 MHz which is shown in Figure 3. This



Maximum Curve		Minimum Curve	
A	(0, 0.05)	a	(0, -0.05)
B	(250, 0.05)	b	(350, -0.05)
C	(325, 0.80)	c	(350, 0.50)
D	(325, 1.15)	d	(400, 0.95)
E	(425, 1.15)	e	(500, 0.95)
F	(500, 1.05)	f	(600, 0.90)
G	(675, 1.05)	g	(650, 0.50)
H	(725, -0.07)	h	(650, -0.45)
I	(1100, 0.05)	i	(800, -0.45)
J	(1250, 0.05)	j	(925, -0.20)
		k	(1100, -0.05)
		l	(1250, -0.05)

Figure 1. ANSI T1.102 - 1993 T1 pulse template

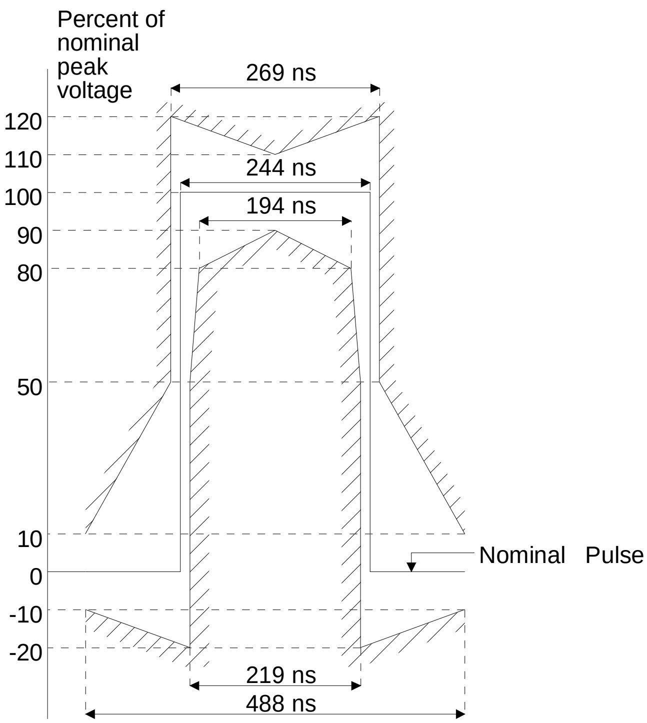


Figure 2. CCITT Rec. G.703 pulse template for 2.048 MHz operation

pulse shape is very similar to the pulse shape shown in Figure 1. As in T1 applications, the pulse is required to meet the template at the digital distribution frame. In this case however, the pulse must meet the mask without scaling. The peak undershoot is specified not to exceed 40% of the peak pulse amplitude.

The remainder of this paper discusses procedures which should be used to accurately measure pulse shapes. There is also a section on measuring pulse imbalance and power transmitted levels.

Reflections

When transmitting a high frequency pulse down a transmission line, a portion of the pulse will reflect wherever it encounters an impedance mismatch. The amount of reflection is proportional to the impedance mismatch; the greater the mismatch, the greater the reflection of the pulse. Even hooking two pieces of wire with different characteristic impedances together will cause re-

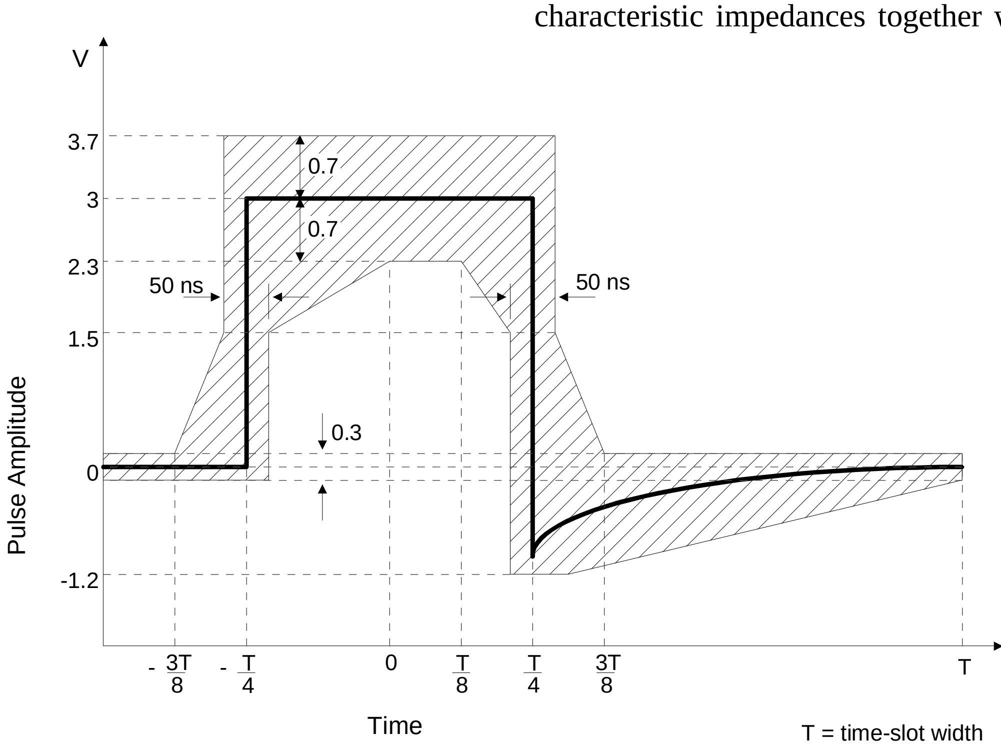


Figure 3 - CCITT Rec. G.703 pulse shape for 1.544 MHz operaton.

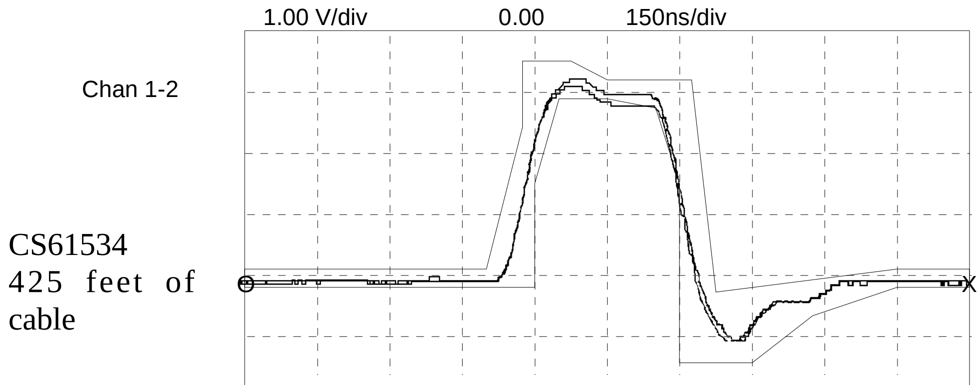


Figure 4 - The smaller pulse's amplitude was reduced by combination with a reflection from a previously transmitted pulse in a repeating 1 out of 2 pattern. The larger pulse is

flections. In order to avoid reflections in a transmission line, impedance mismatches should be avoided, and the line should be terminated with a load that is equal to the characteristic impedance of the line. Proper terminations are every bit as important when measuring pulses in the lab as they are in connecting up the network.

Remember that the load specified for T1 pulse shape measurement is 100 Ω. A commonly used cable in T1 applications is Western Electric ABAM cable which has a characteristic impedance in the neighborhood of 110 Ω. This means that even an otherwise optimal test setup will have a reflection at the load. When this reflection returns to the source, it is likely to experience an even greater impedance mismatch at the driver outputs and therefore have a relatively large reflection component at the source.

One way to reduce reflections at the load is to terminate the desired length of cable with a comparatively long piece of the same type of cable which is then terminated with the load resistor. Such a setup begins to approximate an infinite amount of cable which should provide an optimal impedance match for the test length. In addition, any reflection from the load resistor will be attenuated by the resistive loss of the cable and should be insignificant by the time it returns to the measurement point. *However*, for Central Office equipment, the standard test method is as follows: the cable will be disconnected at the DSX-1, terminated with a 100 Ω load resistor, and measured for compliance with the template. This approach should be used in your lab as well.

Reflections in a lab setup can be minimized by eliminating impedance mismatches wherever possible. The best way to eliminate mismatches is to use the same type of test cable everywhere; that is, from the output of the driver to the input to the oscilloscope. Impedance mismatches due to coax test cables, probes, test leads, or any other leads connected to the line will cause reflections.

Data Pattern

The first step in measuring pulse shapes is to notice that the T1 specifications call for an *isolated* pulse. Unless the pulse is sufficiently isolated, reflections on the line can badly corrupt the measured pulse shape. However transmitting a repeating pattern is necessary to trigger the oscilloscope. A repeating one out of 16 pattern (repeating a 1000 0000 0000 0000 AMI data pattern) is recommended to isolate the pulses to allow reflections to die.

CS61534

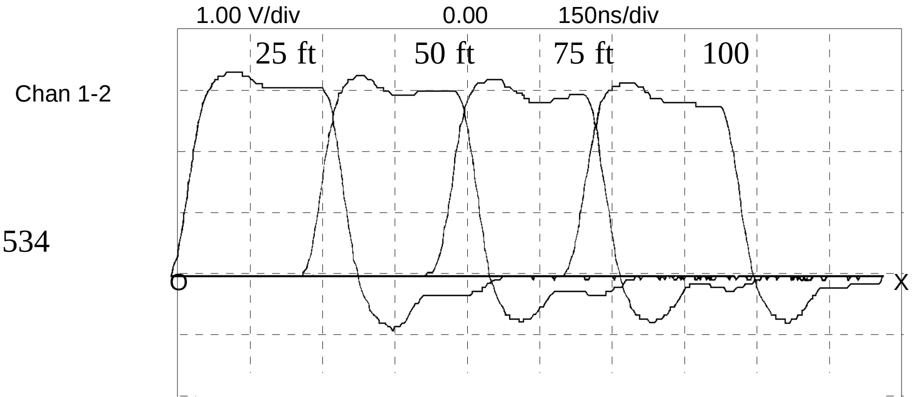


Figure 5 - Four pulse plots are superimposed here to show pulse distortion which is caused by self reflection for cable lenghts of less than 100 feet. Note how the reflection component moves along the pulse as the cable gets longer

Why is the isolated pulse important? Let's assume that a portion of the pulses will be reflected at both ends of the line. As a pulse travels down the line at about 0.66 ft/ns, it will reflect from the termination, reflect from the source, and return to the termination of a 425 ft cable about 1932 ns after it was transmitted, just in time to combine with a pulse transmitted 1296 ns later when it arrives at the load. Depending on the sign of the reflections, this reflected pulse can be either added to or subtracted from the pulse arriving two bit periods later. This is the situation one would observe when transmitting a one out of two pattern as shown in Figure 4. A one out of 16 pattern allows plenty of time between each pulse for reflections to die out of a properly terminated line, allowing accurate measurement of the transmitted pulse.

CCITT specifications for 1.544 MHz operation are very similar to North American T1 specifications in that an isolated pulse is specified and pulses are measured at the distribution frame. There are two significant differences for 2.048 MHz operation. First, G.703 specifies that all pulses must meet the template, not just an isolated pulse, implying that any data pattern is acceptable. Thankfully, the second difference is that pulses are measured at transmitter output rather than after some length of cable, so reflection interaction due to different cable lengths is not a consideration.

Self Reflections

When making pulse shape measurements on short line lengths (generally less than 100 feet), pulses can reflect upon themselves, distorting the pulse shapes of isolated pulses as shown in Figure 5. Nonisolated pulses will likely suffer even greater distortion. Self reflection is unavoidable as long as impedance mismatches exist. Proper termination is crucial when measuring pulse shapes for CCITT G.703 compliance at 2.048 MHz.

Equipment

It is important to understand and identify the sources of error in measurement equipment and choose equipment to minimize any error sources. Since pulses are transformer-coupled to the line, they are differential in nature, so pulse shape measurement should be made in a truly differential manner. Grounding one wire for single ended measurement can introduce uncertainties due to transformer nonidealities, and cable characteristics such as distributed capacitance to a ground, which may be different from the oscilloscope ground. Consider that in making a single ended measurement, one wire is referenced to ground while the other wire is unbalanced.

The exception is transmission over 75Ω coaxial cable at 2.048 MHz. CCITT G.703 states that the outer conductor shall be connected to ground at the output port. Accordingly, measurements of pulse shape should be made with the outer conductor grounded at the oscilloscope input. A single oscilloscope channel is sufficient.

Probes and oscilloscope amplifiers with good balance and high CMRR should be used. Probes, if used, should have low capacitance so pulse distortion is minimized. Unmatched 10X probes may cause significant measurement error due to relative inaccuracies in the 10X attenuation and poor CMRR. Also, the CMRR between two channels of an oscilloscope is rarely specified and is generally very low.

Eliminating the probes altogether is generally preferable. In this case, the same type of cable should be used from the output of the line driver to the input of the oscilloscope. Ideally the load for the cable should be placed at the inputs to the oscilloscope. Some oscilloscopes can be set for internal 50 Ω termination at the inputs. Alternatively, a 50 Ω termination can be connected to both oscilloscope inputs. Providing 50 Ω termination from each wire to ground is analogous to connecting 100 Ω across the two wires, but has the distinct advantage of providing both oscilloscope inputs with signals referenced to the same point rather than having the inputs floating with respect to one another. The 50 Ω resistors should be equal in resistance. Fifty ohm terminating plugs work well and are readily available.

For compliance with CCITT G.703, use 60Ω terminations from both channels to ground when evaluating equipment designed for 120Ω shielded twisted pair, and a 75Ω termination resistor from oscilloscope input to oscilloscope ground for equipment using 75Ω coax. With a little imagination, these terminations can be easily created and attached to the oscilloscope inputs.

Some specifications such as AT&T Publication 43801 call for a 100 Ω resistor connected across TIP and RING. If this setup must be rigidly followed, use either matched differential probes, or the shortest leads possible between the load and the oscilloscope. It may be necessary to use two 50 Ω resistors in series so the oscilloscope can be grounded to a reference point relative to the line so it can trigger. (This is the same as 50 Ω terminators.) These resistors must be accurately matched.

Digital oscilloscopes offer some features such as plotting, amplitude scaling and time and amplitude measurement which makes their use desirable when evaluating pulse shapes. However, be advised that digital oscilloscopes have inherent inaccuracies in the analog to digital conversion and in the sampling process. Most high frequency digital oscilloscopes use either 6-bit or 8-bit A-to-D converters. A six-bit ADC divides a full scale input into only 64 parts, so the quantization error is significant. Any gain error or offset error in the converter, in either channel or between the two channels, will result in amplitude error and distortion of the actual pulse shape. Calibration of a digital oscilloscope is essential to making accurate measurements. Any noise present on the signal or within the converter during the conversion process will result in an error in the conversion. Averaging a fairly large number of samples will help reduce uncertainties caused by noise (quantization or external). Such averaging cannot compensate for ADC nonlinearity errors however.

Sampling uncertainty of digital oscilloscopes must also be considered. If the oscilloscope is sampling at 150 MHz, the sample period is 6.7 ns. For pulse width measurements, the worst case time quantization error is 13.4 ns which can be significant when measuring 244 ns or 324 ns wide pulses. Once again, averaging several samples effectively eliminates any error due to sampling uncertainty.

Digital oscilloscopes are very useful in evaluating pulse shapes. However, the averaging process will tend to mask pulse-to-pulse variations that are undesirable. It is advisable to check the results on an analog oscilloscope which is in calibration.

A oscilloscope with a delayed triggering feature is essential. Delayed triggering allows precise positioning of the isolated pulse on the screen, and also allows the user to amplify and observe a small portion of the pulse which may require greater scrutiny. Delayed triggering also allows for fairly easy comparison of positive and negative pulses for verifying that pulse imbalance requirements are met.

No matter which instruments you have available, a proper test setup is essential. Three good measurement techniques are as follows:

1) An active differential probe such as the Tektronix P6046 allows differential signal processing at the probe tip with very high CMRR. Only a single channel on the oscilloscope is required thus removing CMRR considerations at that point. This probe offers distinct advantage when using a digital oscilloscope in that the addition of the quantization errors of the two channels is avoided. For both analog and digital oscilloscopes channel-to-channel inaccuracy and imbalance are no longer an issue and CMRR is much better.

2) Use a true differential amplifier with good common mode rejection such as the Tektronix 7A13. Run the test wire all the way to the diff amp's input (avoid using test leads for interconnection) and terminate the line at the inputs with 50Ω (60Ω for CCITT 120Ω shielded twisted pair). The only probes that should be considered for use in such measurements are matched probes with high CMRR like the Tektronix P6055. When using probes, make sure they are calibrated.

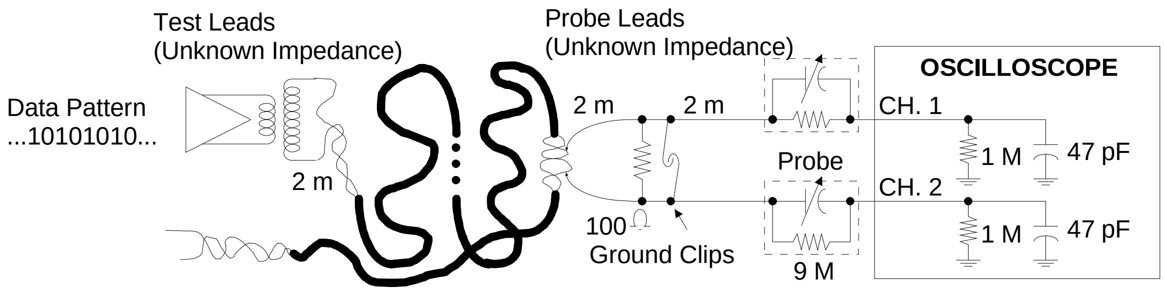
3) As previously discussed, using a standard two channel oscilloscope has some disadvantages, but may be the only method available for pulse shape measurement. Once again, it is best to run the test wire all the way to the oscilloscope inputs and terminate the line at the oscilloscope inputs. (If probes are necessary, use matched and calibrated probes.) TIP should be connected to one channel and RING to the other channel. Invert channel 2 and add it to channel 1. Always set the oscilloscope inputs for DC coupling to keep the internal oscilloscope capacitors out of the circuit. The amplifiers should always be in the calibrated configuration.

The following figures illustrate pulse measurement techniques and show an example of the error that can be caused by poor techniques. Figures 6 and 7 show some DOs and DON'Ts for measuring pulse shapes. Figure 8 shows the effects of terminating the line with a floating 100 Ω resistor and measuring the signal across the resistor with unmatched probes.

Pulse Shape Evaluation

The pulse displayed on the oscilloscope must be checked for amplitude and conformance to the pulse template. The pulse amplitude is measured at midpulse. The method for checking for conformance with the template depends on the specification. For CCITT specifications, the pulse must fit the template with no scaling allowed. DSX-1 specifications allow the pulse to be scaled by a linear factor to fit within the template. Figure 9 shows a pulse which has been aligned, scaled and plotted from a digital oscilloscope onto a template.

What's Wrong With This Picture?

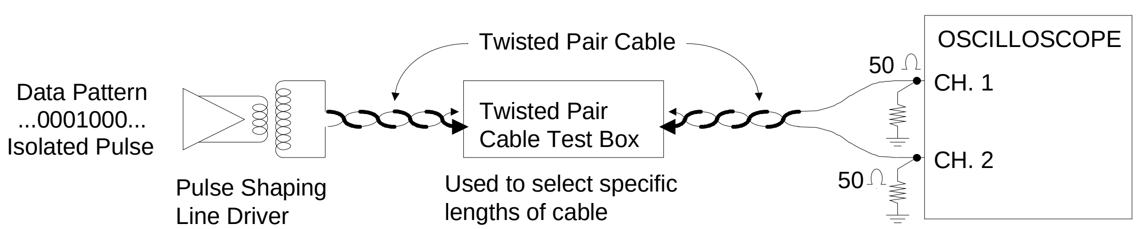


- Numerous impedance mismatches - reflections galore
- Data pattern does not provide an isolated pulse.
- Floating termination - no ground reference for measurement
  (but required by 43801)
- Undetermined tail on cable - improper termination
- Are probes precisely 10:1?
  Have they been calibrated correctly?

Figure 6 - How NOT to measure pulses.

PULSE MEASUREMENT USING TWO CHANNEL OSCILLOSCOPE

- Avoid reflections due to impedance mismatches
  - Despite taking precautions, neither end of the cable will be ideally terminated so watch for reflections from previous or current pulse
  - Use the same type of cable where ever possible



- Oscilloscope should be DC coupled
- High-resolution, digital oscilloscopes are nice because pulses can be precisely scaled and plotted making evaluation easier
- Test cable terminated at oscilloscope input

Figure 7 - Recommended pulse shape measurement test configuration and guidelines.

CS61534
350 feet of cable

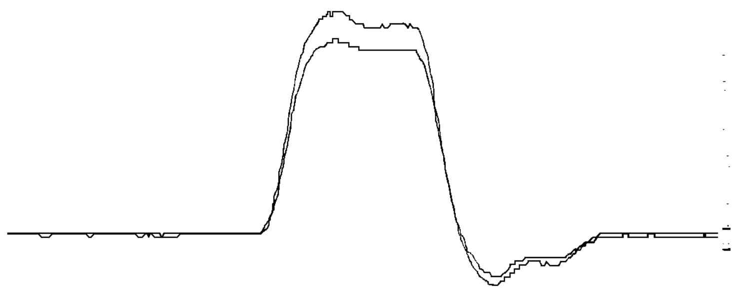


Figure 8 - Mistermination and gain error can have significant effect on pulse amplitude. The larger pulse results from the use of probes which are not well matched,

When evaluating pulse amplitude and template conformance, be sure to test over the line driver's specified operating voltage and temperature ranges. For amplitude measurements, setting the oscilloscope for 0.5 V/div is best, while 1.0 V/div is convenient for template matching.

Creation of the pulse template against which the displayed pulse is to be evaluated is worthy of consideration. It is important that the template have the correct proportions so that the pulse may be accurately evaluated. In some cases, the template must be created to an absolute scale so it can overlay the pulse or have the pulse plotted over it. Reproduction of the pulse template is very tricky since copiers tend to distort the original. A first generation photocopy can have enough distortion to render the copied template useless. Only through painstaking effort can a useful copy be produced (and if this method is used, make an abundant number of copies once the copied template is accurate).

To evaluate a pulse displayed on the oscilloscope's CRT, create a template which is scaled to the oscilloscope grid on a transparency, align the template to the grid and affix the template to the CRT. Center the pulse in the template. Scaling the pulse by adjusting the amplifier gain is only possible when using a single channel oscilloscope, a differential amplifier, or a digital oscilloscope. When using a two channel oscilloscope, method three, do not use the amplifier's gain adjustment (uncalibrated) to adjust the pulse

CS61574
400 feet of cable

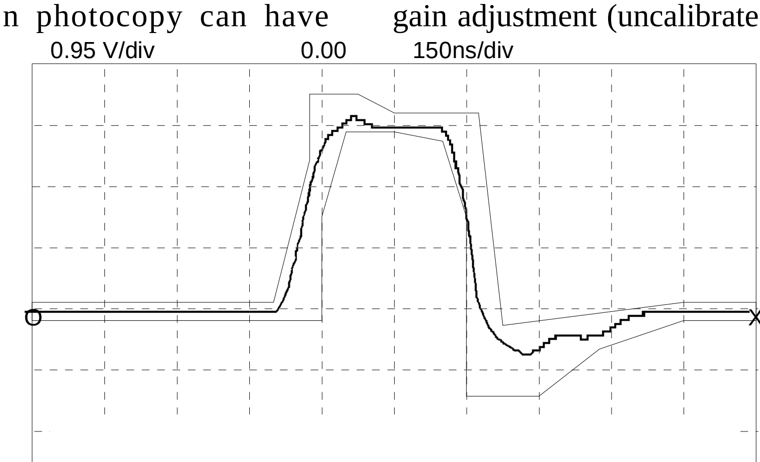


Figure 9 - Plot of a properly terminated, isolated pulse from a CS61574. Note that the amplitude scaling feature of the digital 'scope was used to boost the pulse amplitude

amplitude to match the template. Adjusting one channel only results in a nonlinear change in the pulse. Additional templates scaled to larger and smaller amplitudes are required.

Once everything is satisfactorily aligned, take a picture. It is much easier to describe, complain about or compare pulse shapes on hard copies. A hard copy also provides a permanent record for future reference.

Most digital oscilloscopes have the capability to transfer the image displayed on their screen to a plotter. There are three basic methods of plotting available. The most sophisticated method allows entry of the template parameters to the system so the template is plotted to the appropriate scale along with the pulse.

A second method offered by some systems, allows the operator to align the oscilloscopes plot dimensions to an independently created grid. This method allows the user to create the template to a convenient scale. Using the plotter, the corner points of the oscilloscope's grid are physically aligned with the corner points of the grid on the plotter paper. The plotter then scales the plot of the oscilloscope's grid to fit the grid on to plotter paper. This technique is especially good when using photo copies of an original grid and template. Since the plot is scaled to fit, copier distortion is irrelevant.

The third method involves generating a template for a plotter without a scaling feature. The template must be created to exactly the same size as the plotter's rendition of the oscilloscope grid, and positioned on the plotter paper at precisely the point at which the oscilloscope's display is plotted. The biggest problem here is creating a sufficiently large number of blank templates which are the right size and in the right place so they will line up with the plot. The alternative is to generate a single template on a transparency to overlay the plots, but this approach makes it difficult to evaluate a large number of plots.

An especially nice feature of digital oscilloscopes is the gain scaling which allows the user to linearly scale the pulse either up or down to fit a fixed template. For instance, if the pulse is a little short, the gain may be set for 0.95 V/div, thereby making the pulse a little taller. The horizontal and vertical settings are usually plotted along with the trace, so these settings are recorded as well. Take care to maintain the time scale to a fixed value which corresponds with the template. Pulse width scaling is not allowed.

A note about the DSX-1 pulse template: the minimum pulse width allowed is 300 ns, the maximum is 400 ns. If the pulse width is based on a 50% duty cycle of a 1.544 MHz clock, the pulse width will be 324 ns. This allows only 12 ns of margin to either side of the template's minimum curve. When compared to the template, the pulse will look narrow, but it is really all right. (Presumably, the minimum allowable pulse width is kept wide to help maximize receiver jitter tolerance.) The opposite situation exists for CCITT G.703 pulse width specifications which range from 194 ns to 269 ns. A 50% duty cycle pulse, 244 ns, is a little on the wide side.

Positive/Negative Imbalance and Power Levels

Pulse imbalance and signal power level measurement are both intended to ensure that there is no significant DC offset at the termination of the line. Since positive to negative pulse imbalance can result in more power at 1.544 MHz relative to the power at 772 kHz of an all ones signal, meeting the power level specifications also means pulse imbalance is satisfied.

An oscilloscope can be used for checking pulse imbalance between the positive and negative pulses. CB-119 calls for less than 0.5 dB difference between the power of positive and negative pulses. Power is roughly the product of the square of the pulse height and pulse width, so both must be investigated. There should be less than 200 mV difference in amplitude of otherwise identical positive and negative pulses. Variation in the widths of positive and negative pulses of only a few nanoseconds will also result in some pulse imbalance. One good method for comparing positive and negative pulses is through the use of a digital oscilloscope which is capable of integrating the area of a pulse; this makes for straightforward comparison of the positive and negative pulses.

Measurement of power levels in an all ones pattern is best accomplished with a specialized instrument such as the Hewlett Packard 3586B (HP 3586A for CCITT). This instrument can measure the power in a 2 kHz band at both 772 kHz and 1.544 MHz as required by CB-119. The power in the 2 kHz band at 772 kHz must be between 12.4 dBm and 18.0 dBm, and at least 29 dBm greater than the power in a 2 kHz band at 1.544 MHz . CCITT 1.544MHz specs require the power in a 3 kHz band at 772 kHz be between 12.0 dBm and 19.0 dBm and at least 25 dBm greater than the power in a 3 kHz band at 1.544 MHz. CCITT PCM-30 specs allow ±5% variation in the heights and widths of positive and negative pulses. When using this instrument, take care to terminate the line driver properly. The input impedance of the HP 3586 is selectable but 100 Ω input impedance is not offered. A HP 15508B converter will provide a 110 Ω balanced termination for the line and 75 Ω unbalanced impedance for the input of the instrument.

Alternatively, power levels can be measured using a spectrum analyzer. An estimation of the power at 772 kHz can be made by selection of the appropriate resolution bandwidth of the spectrum analyzer. As long as the power at 772 kHz meets the specification with reasonable guardband, and the difference in amplitudes of the power at 772 kHz and 1.544 MHz is several dB in excess of the spec, precision measurements are probably unnecessary.

• Notes •