X3T9.2/90-134

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To: Larry J. Lamers, Maxtor corporation
Chairman X3T9.2 cable working group

From: Jim Fiala, 3M Corporation

Date: August 24, 1990

Subject: Rough draft of cable test parameters, test procedures and test philosophies

The following document describes various tests that may be performed on cable intended for use with SCSI III systems. Also shown are recommended value ranges to insure a reasonable ability to work with the SCSI system. Each test includes a statement regarding the philosophy behind the test. Most specifications do not have such a statement, however I feel that such a statement enhances the understanding of why certain tests are performed and the reasoning behind the value limits.

There are 2 distinct categories of tests. The first are performance tests and are designed to indicate the relative performance of a cable. Generally the lower the number the better the performance. For example a cable with 5 dB/100 ft attenuation at 100 MHz would be superior to a cable with 10dB/100 ft. A cable with .5ns/20 ft rise time degradation would be superior to a cable with 1ns/20 ft degradation.

The second category of tests are characterization tests. These tests determine the base characteristics of the cable and may not be indicative of cable performance, for example capacitance, inductance, propagation delay and impedance. However, a sub part of these cable characteristics would be delta variation from wire to wire within the same cable. This variation of base parameters would be indicative of a cable's "quality of construction" and generally the smaller the number or variation the better the performance and quality of the cable.

Each test may have several methods and types of equipment that may be used to perform the test and obtain numerical results. Where multiple test procedures are shown, the first test method will produce the most accurate and repeatable results. It should be expected that when the same cable sample is tested utilizing the different test procedures that the results WILL NOT be the same. By utilizing the first test procedure any cable sample used for "round robin" testing should produce relatively close numerical values between the different manufacturers.

After reviewing the test procedures and values, the test values may be readily converted to metric equivalents. I would also be willing to test cable samples utilizing the first test procedures shown so that other cable manufacturers can correlate their test results on the same sample.

Preparation of cable samples prior to performance and characterization tests.

The preparation procedures outlined here are intended for SCSI performance and characterization tests when either round shielded discrete twisted pair cable or flat shielded cable is to be used and tested in the UNBALANCED mode. Cable that will be used in the balanced mode requires totally different preparation, test procedures and performance specification numbers.

Accurate and careful cable preparation is essential for obtaining repeatable and accurate cable test results. By using the cable preparation techniques outlined here and the cable testing procedures described later, each testing organization should be able to obtain test results and values within a fairly narrow range when testing the same cable. Obviously equipment type, calibration and operator interpretation will affect test results, however the first test procedure outlined in each test sequence is designed to minimize these variations.

Cable preparation for round shielded discrete twisted pair.

1. Cut sample cable length to 20' 3" within 1/4"

2. Remove 1.5" of outer jacket at each end.

3. Place a band of thin .001" to .003" thick by 1/2" wide adhesive backed copper foil sheet around the outer jacket with adhesive side towards jacket.

4. Pull the copper braiding shield over the copper band and jacket. Tape may be used to hold the copper braiding in place.

5. Solder the braiding to the copper band.

6. Trim any filler or aluminum shielding material.

7. Select one wire of each pair for grounding to the braiding and copper band. Tip, for easier wire identification choose the solid color (white, tan or brown) wire with color stripe for grounding. For example; on Madison cable the following sequence would apply.

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PAIR	WIRE TO GROUND	SIGNAL WIRE
1	white with tan stripe	tan with white stripe
2	white with brown stripe	brown with white stripe
3	white with pink stripe	pink with white stripe
4	white with orange stripe	orange with white stripe
5	white with yellow stripe	yellow with white stripe
6	white with green stripe	green with white stripe
7	white with blue stripe	blue with white stripe
8	white with violet stripe	violet with white stripe
9	white with gray stripe	gray with white stripe
10	tan with brown stripe	brown with tan stripe
11	tan with pink stripe	pink with tan stripe
12	tan with orange stripe	orange with tan stripe
13	tan with yellow stripe	yellow with tan stripe
14	tan with green stripe	green with tan stripe
15	tan with blue stripe	blue with tan stripe
16	tan with violet stripe	violet with tan stripe
17	tan with gray stripe	gray with tan stripe
18	brown with pink stripe	pink with brown stripe
19	brown with orange stripe	orange with brown stripe
20	brown with yellow stripe	yellow with brown stripe
21	brown with green stripe	green with brown stripe
22	brown with blue stripe	blue with brown stripe
23	brown with violet stripe	violet with brown stripe
24	brown with gray stripe	gray with brown stripe
25	pink and orange	orange and pink

8. Trim each ground wire to 1/2" exit length from jacket, then strip wires as close to jacket as practical. These wires are then soldered to the copper foil and braiding.

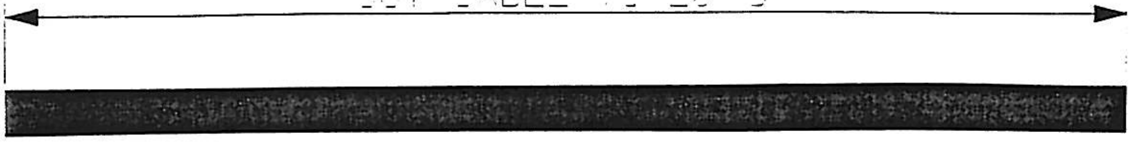
9. The remaining signal wires are then stripped of insulation 1/4" and tinned.

10. This step is optional, but highly recommended. With the cable ends held vertically, apply GE self leveling adhesive sealant RTV 112 in the area where the signal wires exit from the jacket. For the first 1/2 hour after application the RTV slowly flows into the wire bundle, after curing for 24 hours the RTV will lock the wires in place, thus stabilizing the cable characteristics for testing. This step helps increase the test repeatability if samples are sent "round robin".

Shielded flat cable preparation.

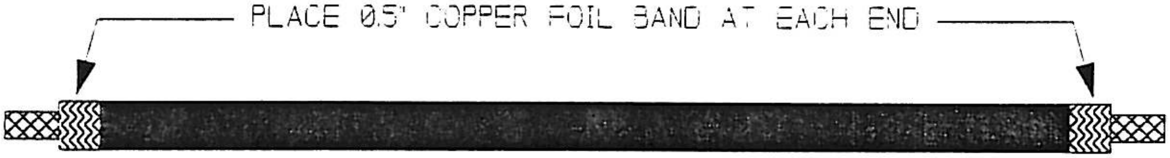
1. Cut sample cable to 20′ 3″.
2. Remove 1.5″ of outer jacket at each end.
3. Remove 3/4″ of shielding at each end.
4. Separate wires to shielding.
5. Strip each wire 1/4″ and tin ends.

CUT CABLE TO 20' 3"

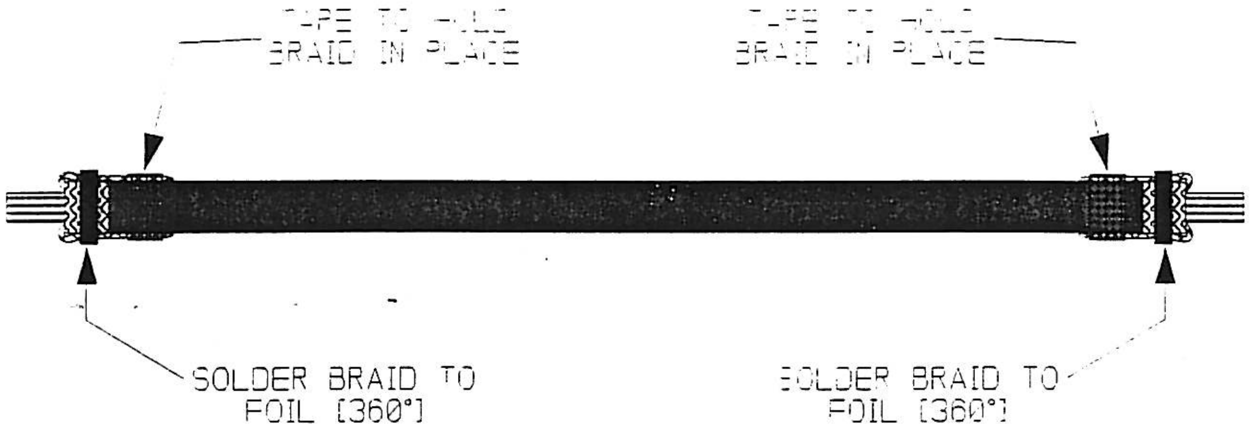


REMOVE JACKET 1.5" TO EXPOSE BRAID AND WIRE

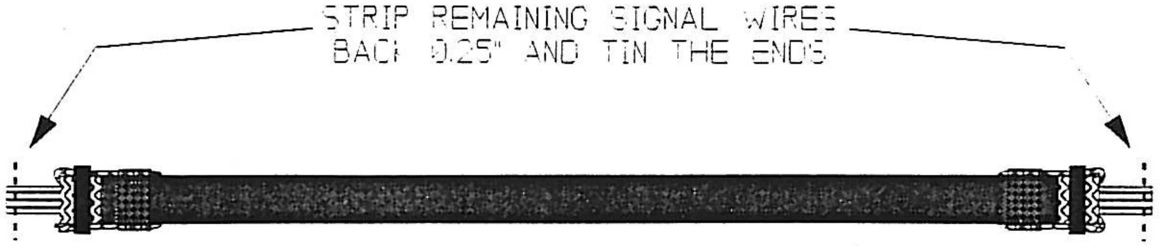
PLACE 0.5" COPPER FOIL BAND AT EACH END



PULL STRANDED COPPER BRAID
OVER FOIL BAND AND JACKET


TAPE TO HOLD BRAID IN PLACE
TAPE TO HOLD BRAID IN PLACE
SOLDER BRAID TO FOIL [360°]
SOLDER BRAID TO FOIL [360°]


TRIM ALL GROUND WIRES TO 0.5" LONG
TRIM ALL GROUND WIRES TO 0.5" LONG
STRIP ALL GROUND WIRES AS CLOSE AS POSSIBLE AND SOLDER HERE
STRIP ALL GROUND WIRES AS CLOSE AS POSSIBLE AND SOLDER HERE


STRIP REMAINING SIGNAL WIRES BACK 0.25" AND TIN THE ENDS

Cable performance tests

1. Rise time degradation (RTD).

2. Square wave voltage attenuation (SWVA).

Rise time degradation measurement.

Test philosophy

RTD of digital data signals causes increased noise susceptibility, jitter and timing errors. Therefore the lower the RTD introduced by a cable the more reliable the data transfer will be. There are 2 variables that cause cable RTD.

1. The length of cable.
2. The transmission quality of a cable.

Since RTD is not necessarily linear over cable length then RTD should be measured on a cable sample that is the maximum length to be used in a system, in this case 20 ft. A transmission line quality comparison of various cables can be made by measuring RTD on different cables of the same length. The lower the RTD the better the transmission line quality, and the better the cable will perform in an operating system.

Factors influencing RTD are dielectric properties, propagation characteristics, uniformity and consistency of construction and signal bandwidth. Note that contrary to popular belief, at fast data rates capacitance is not a factor in RTD. High capacitance does not necessarily equate to a high RTD. For example; a typical 28 gauge .050 spaced flat ground plane cable may have an RTD of 1.2 ns over 10 ft and a capacitance of 22 pf/ft however, a coax cable or 3M PFC may have an RTD of .1 ns or less per 10 ft and a capacitance of 30 pf/ft. Ordinary 28 gauge unshielded .050" flat ribbon cable has a relatively low capacitance of 13 pf/ft yet a high RTD of 1 ns/10 ft.

The RTD is a direct indicator of the signal bandwidth of a cable, the lower the RTD the less attenuation occurs at high frequencies and the less rounding occurs on the square wave pulse used for this RTD test.

RTD cable test procedure

Typical test equipment used.

Pulse generator: HP models 8007B, 8082A or equivalent

High frequency scope: 350 + MHz bandwidth, Tektronix 485, Tektronix 7834 with 7S12 sampler - S4 head - S53 trigger recognizer, or equal.

High frequency probes: Tektronix P6201 active FET probe. This probe is highly recommended for transmission line testing as it has a bandwidth of 950 MHz, rise time rating of .9 ns and 1 to 1 voltage measurement at 100 k ohms input impedance and will non-invasively measure cable.

Test procedure

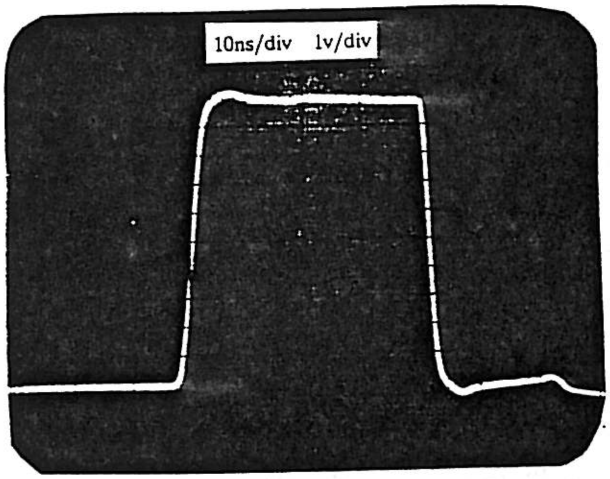
1. A signal wire and ground of the cable to test are connected to the pulse generator output, preferably though a suitable test fixture. I have a solid copper fixture design which is excellent for these and other tests). The scope probe is inserted into the fixture or placed directly at the beginning of the cable. Caution, the probe ground connection to the cable shield cannot be any longer than 1/2".

2. The pulse generator is adjusted to produce a 5 volt 40 ns wide approximately 2.5 ns rise time signal, at a repetition rate of about 1 MHz. The scope horizontal is then decreased to 500 ps/div, at this time the rise time can be exactly adjusted to a 2.5 ns rise time measured at the 10% and 90% points on the scope. This rise time adjustment must be done vary carefully and precisely for accurate results. Note that there is nothing magic about the 2.5 ns rise figure. This figure was chosen as being must convenient for alignment when the scope horizontal is magnified.

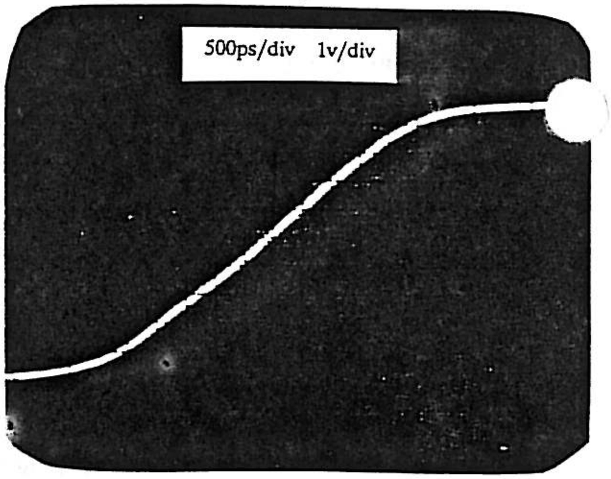
3. The scope probe is then moved to the far end of the cable which may be terminated in the characteristic impedance of the wire being tested (termination is not absolutely necessary but nice). The scope vertical gain is then adjusted such that the output pulse measures exactly 5 volts on the scope. The scope horizontal is then changed to 500 ps/div and the 10% to 90% rise is then noted.

4. The value of rise time degradation for the 20 ft of cable would be the input signal rise time (2.5 ns) subtracted from the output signal rise time. For example, if the output rise time measured 4.2 ns then the rise time degradation for 20 ft of cable would be 1.7 ns (4.2 minus 2.5 = 1.7 ns).

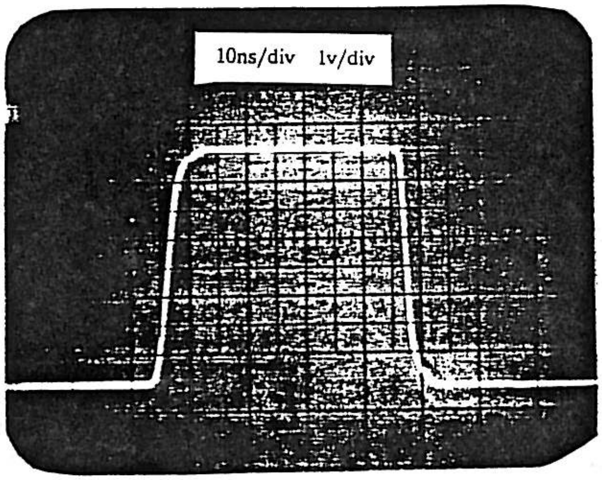
RTD SCOPE TRACES



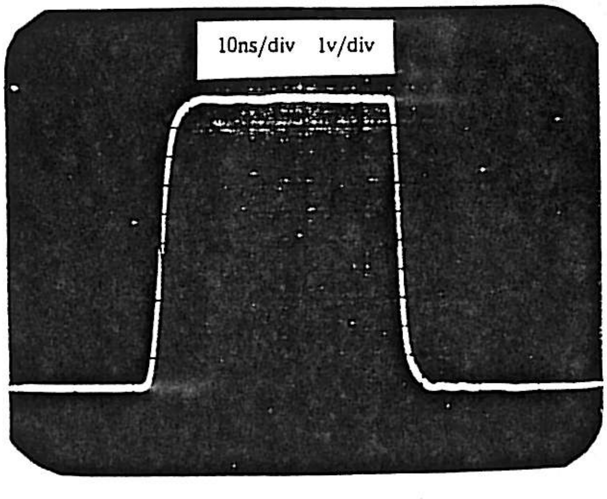
Cable input waveform adjusted
to 5v at 0% to 100%.



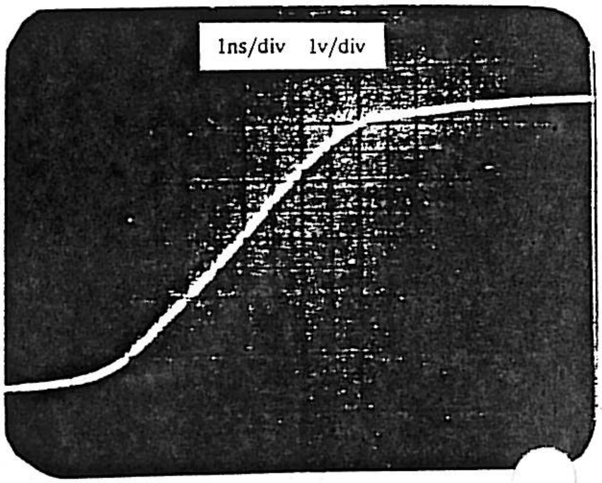
Cable input rise time adjusted
to 2.5ns at 10% to 90%



Cable output waveform



Cable output waveform verticle
gain adjusted to produce 5v
0% to 100%



Cable output waveform showing 10% to
90% rise time of 4ns. Therefore RTD
of cable = 1.5ns/20 ft

Square wave voltage attenuation measurement

Test philosophy

SWVA and RTD are the best test methods to indicate the performance levels of digital data, transmission line cables. These 2 tests are the best simulations as to what happens to digital data when traversing the cable. The factors affecting SWVA are wire gauge, dielectric material and cable construction. All these factors play a role in determining SWVA, therefore generalizations should not be made regarding one factor alone. For example, normally one would think that a 28 gauge cable would have a lower SWVA than a 30 gauge cable, and in some cases this would apply, but not all. A 3M PFC cable would have a lower SWVA than an ordinary 28 gauge flat ribbon cable, but a 26 gauge flat ribbon cable would have a lower SWVA than the 28 gauge flat cable. This indicates that dielectric material and construction also play a role in determining SWVA.

The SWVA test involves adjusting the pulse generator to a 5 volt level with the cable attached. It will be noticed that when different impedance wires are attached to the pulse generator that to maintain a 5 volt input level the pulse generator level must be increased to hold this level when lower impedance wires are connected. Under real world usage situations the digital cable drivers do not compensate when lower impedance lines are connected, therefore cable output voltage levels will drop correspondingly. Since this SWVA test is only designed to measure the SWVA of the cable itself, consideration must also be given, in an actual system, to the SWVA caused by lower impedance wires.

If a lower impedance cable has a lower SWVA than a higher impedance cable, then usage of the lower impedance cable may not be detrimental to system performance, especially if the lower impedance cable has better transmission line properties such as rise time degradation. For example if an operating system has an open circuit voltage of 10 volts and a 100 ohm cable is attached, the voltage may drop to 8 volts. If a 50 ohm cable is attached the voltage may drop to 6 volts. However, if the 50 ohm cable has an SWVA of 2 volts and the 100 ohm cable 4 volts, the net result in an operating system would be that both cables would produce an output signal of 4 volts.

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SWVA cable test procedure

Typical test equipment used.

The same as used to measure RTD.

Test procedure

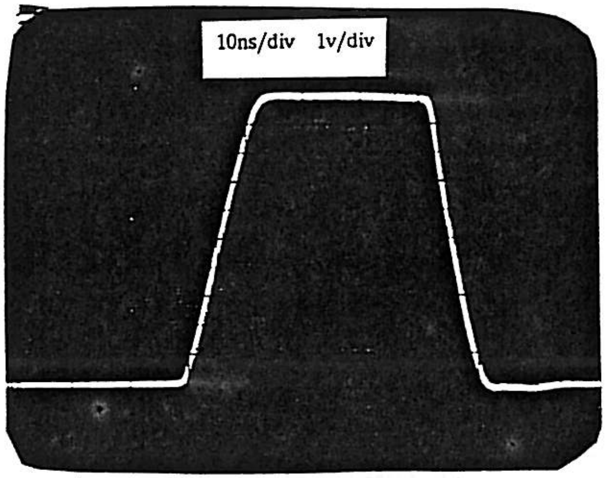
1. A signal wire and ground of the cable to test are connected to the pulse generator through a suitable test fixture. The scope probe is inserted into the fixture or placed directly at the beginning of the cable.

2. The pulse generator is adjusted to produce a 5 volt 40 ns wide pulse with a rise time of around 8 to 10 ns at a repetition rate of about 1 MHz.

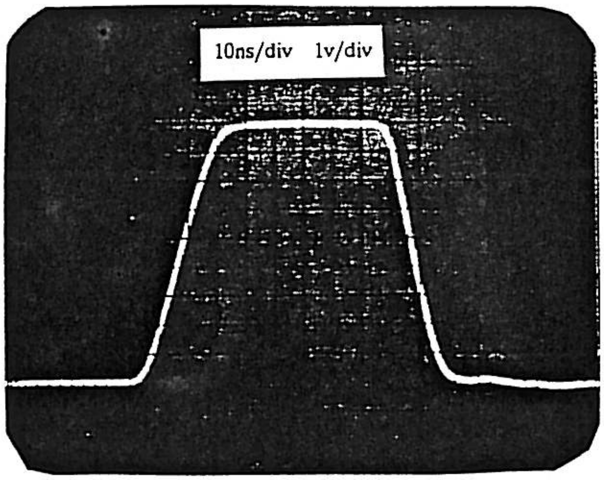
3. The scope probe is then moved to the far end of the 20 ft cable sample, which should be terminated in its characteristic impedance. An alternate termination would be to use a value that is actually going to be used in the same system as the cable such as 110 ohms or 130 ohms. The voltage level of the square wave is then noted.

4. If the output voltage of the cable reads 4 volts then the SWVA for this 20 ft sample would be 1 volt or expressed as a percent of the input voltage 20%. The lower the % SWVA the better the transmission line performance of the cable in a digital data transmission system.

SWVA SCOPE TRACES



Cable SWVA waveform adjusted
to 5v



Cable output waveform showing
4.5v output. SWVA = .5v/20ft
or 10%

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Cable characterization tests

1. Propagation delay expressed in ns/ft
1a. Propagation skew

2. Capacitance expressed in pf/ft
2a. Capacitance skew

3. Impedance expressed in ohms
3a. Delta impedance variation

4. Inductance expressed on uh/ft

Propagation delay and skew measurement

Test philosophy

Propagation delay (PD) is the time it takes for a signal to traverse the length of cable. Generally in long cable lengths the actual value of delay time is not critical, however what is critical is the variation of PD from one wire to the next in the same cable. This variation is commonly referred to as PD skew. The lower the skew the better the uniformity and quality of the cable construction.

There is a direct relationship between PD, % velocity and effective dielectric constant (EDC). If you know one number then you automatically know the other 2. Note that effective dielectric constant may or may not be the same as the dielectric constant of the cable insulating dielectric material. For example PVC raw material may have a dielectric constant of 3.2, however when used to make a flat ribbon cable, because some of the signal travels in air, the effective dielectric constant may be 2.2.

It is easy to be fooled into thinking that the ranking of cables would be determined by effective dielectric constant, with the higher number being poorer quality cable and the lower number being better quality. This ranking only applies to like constructed cables. For example a coax cable with an 84% velocity factor (EDC 1.42) would be an excellent transmission line and have a very low loss. Any like constructed coax cable less than 84% would have higher loss and not perform as well as a transmission line. A teflon flat ribbon cable with a velocity of 89.5% (EDC 1.25) would have higher losses and be a poorer transmission line than the coax cable.

If you take the teflon flat ribbon cable and surround it with an intimate shield then the EDC may become 2.2 (67.4%) which is very close to the dielectric constant of the teflon itself. This cable construction would now be an excellent transmission line, although not as good as the coax cable. The point here is that by measuring PD you now know EDC or % velocity and can use this information to determine the quality of a transmission line.

When ranking cables the following principles would apply. The best cable would be one in which the EDC would be closest to the dielectric constant of the insulating material. Then within that group the best cable would be the one with lowest EDC. The best transmission lines are ones where all of the signal is forced to remain within the cable dielectric (insulating material), then the best cable would the one using the lowest dielectric constant insulating material. This by the way is the principle behind the 3M PFC cable where the shield is adhesively bonded to the cable dielectric thus preventing any of the data signals from leaving the insulating dielectric material. The EDC of the PFC cable is very nearly equal to dielectric constant of the TPE insulation.

PD cable test procedure

Typical test equipment used.

Signal analyzer: HP network analyzer 3577A, 8753A or equal device, alternates would be an RF signal generator, frequency counter and RF voltmeter or time domain reflectometer or pulse generator and dual trace oscilloscope.

Signal probes: Tektronix P6201 active FET probe recommended.

PD test procedure 1

1. A signal and ground wire of the cable to be tested are connected to the output of the network analyzer through a suitable fixture. The pickup probe feeds back to the network analyzer and is positioned at the beginning of the test cable. Note the probe ground should be kept as short as possible and connected to the test cable copper shield band.

2. The network analyzer is set to a start frequency of 14 MHz and a stop frequency of 17 MHz. This corresponds to a PD of from about 1.5 ns/ft to 1.7 ns/ft.

3. The far end of the wire beginning tested is shorted to the shield copper band at its end. This now creates a transmission line that nulls at 1/2 wavelength intervals. By reading the frequency of the first null the PD for 20 ft of cable can be calculated from the following formula.

First null 1/2 wavelength

$$\boxed{PD\ (nS) = \frac{1}{FREQUENCY\ (MHz)} \times 500}$$

Second null 1 wavelength

$$\boxed{PD\ (nS) = \frac{1}{FREQUENCY\ (MHz)} \times 1{,}000}$$

The PD per ft can be easily calculated by dividing the above number by the length of the cable (20 ft).

4. This is an extremely accurate and repeatable way to measure PD of cables. Also by using different lengths of cable and different multiple wavelength frequencies the change in PD versus frequency can be obtained. A movement of the probe pickup point 1/10" corresponds to about a 10 KHz frequency change. Therefore you can expect the resolution of this test to be better than 20 ps. Something that cannot be achieved by using a TDR.

Test 1a

1. The same test as above may be performed by using an RF signal generator, frequency counter and RF voltmeter or scope. This equipment substitutes for the network analyzer.

2. The RF signal generator is manually adjusted around the frequency range from 14 MHz to 17 MHz while watching the RF voltmeter for the null point. The frequency of the null is read from the frequency counter connected to the signal generator. This frequency corresponds with the null frequency observed when using the network analyzer. The same calculations used with the network analyzer are used to determine the PD.

Test 1b

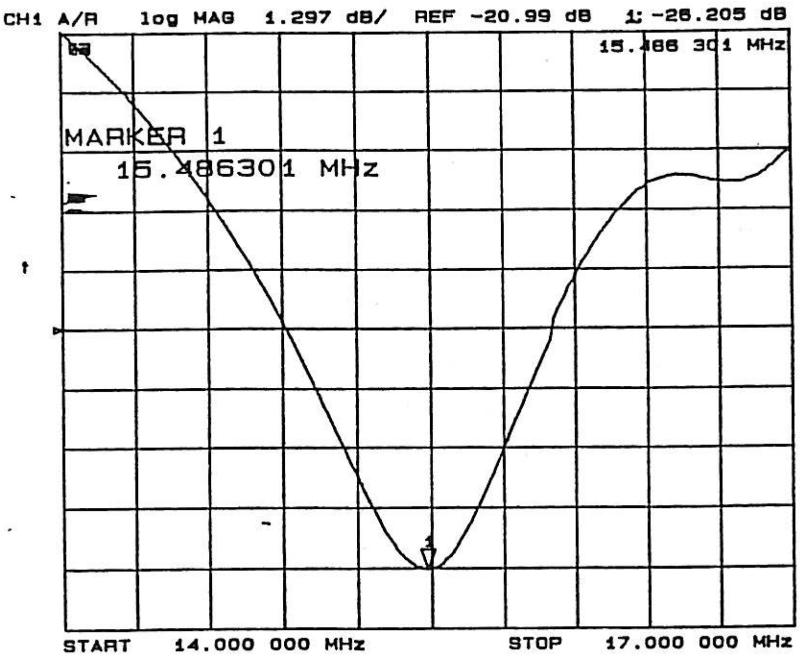
PD may be determined by using a TDR or pulse generator and dual trace scope. However using this equipment produces extremely variable results subject to operator interpretation. Digital readout TDR'S may be giving digital PD answers to .01 ns but these values can easily be off by 1 to 2 ns over a 20 ft test cable. The problem occurs because the cables being tested are high loss cables with severe RTD and SWVA. These distortions make it impossible to accurately measure the leading edge of the test pulse after traversing 20 ft of cable. As was noted in the RTD test, the leading edge of the test pulse dramatically changes from the beginning to the end of the 20 ft length of cable.

EDC, % velocity and PD relationship

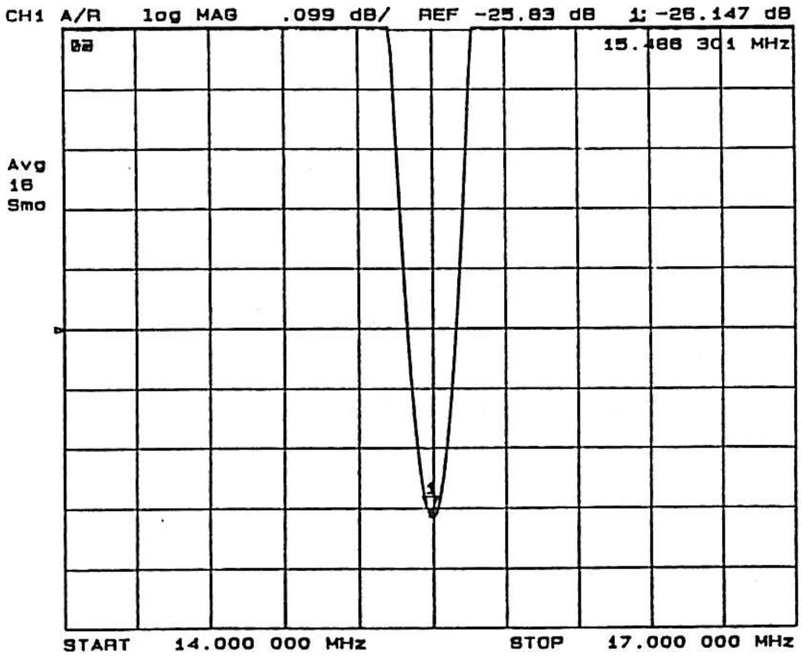
PD	VELOCITY	EDC
1.4ns	72.6%	1.89
1.45ns	70.1%	2.03
1.50ns	67.6%	2.17
1.55ns	65.8%	2.32
1.60ns	63.5%	2.47
1.65ns	61.6%	2.63
1.70ns	59.8%	2.79

PD skew measurement

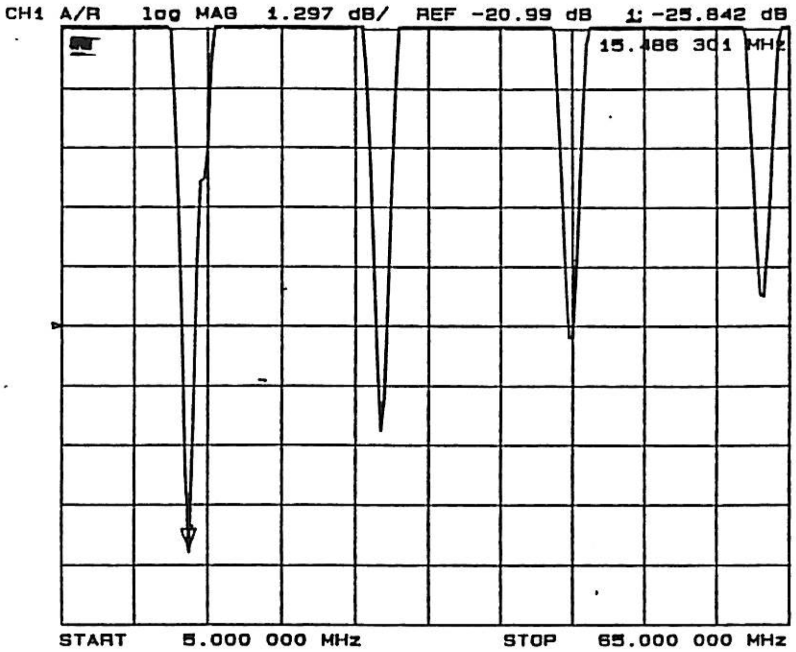
PD skew is obtained by simply measuring all of the signal wires in a test cable for PD. The highest and lowest numbers are subtracted from each other the result is the total skew or PD variation in that cable sample. The cables with the lowest skew represent the best transmission lines.



Network analyzer showing first 1/2 wavelength null of 15.486301 MHz which =32.2866 ns/20 ft or 1.614 ns/ft on the cable sample



dB/div on network analyzer changed to show how deep and accurate the 1/2 wavelength null point is



Network analyzer showing nulls at 1/2, 1, 1 1/2 and 2 wavelengths

Capacitance and skew measurement

Test philosophy

Capacitance is one of the easiest parameters to measure accurately and with repeatability. There are a few cautions. The shield and ground wires should always be connected to the high terminal and the signal wire to the low terminal. The best test frequency for cables being used for transmission lines is between 100 KHz and 1 Mhz.

The actual value of capacitance is not as important as the variation or skew. You can also see from the chart on page 17 that PD and capacitance on any one test cable are directly related to each other. The higher the capacitance the slower the PD of the cable (higher PD number). The lower the capacitance the faster the cable PD. If you chart your PD and capacitance as shown on page 17 and this relationship does not hold , then you know either or both your test values of PD and capacitance are incorrect. Generally the error occurs in the measurement of PD, when trying to use a TDR or dual trace scope for the PD measurement.

High capacitance in itself does not indicate a poor transmission line cable, however it does indicate a lower impedance. If a systems line drivers are current limited then a high capacitance or lower impedance cable will reduce the voltage being impressed on the input to the cable. This lower input voltage means that the output voltage will also drop proportionately thus reducing the noise margin of the cable.

Capacitance cable test procedure

Typical test equipment used

4 or 5 terminal digital LCR meter, HP 4275A or equal.

Test procedure

1. The digital LCR meter is set for a test frequency between 100 Khz and 1 MHz. The ground ring at one end of the test cable is attached to the high output of the LCR meter. The signal wire is attached to the low output. Capacitance is displayed on the LCR digital meter in pf/20 ft. To obtain pf/ft simply divide the reading by 20.

2. Capacitive skew is obtained by measuring all of the signal wires in a test cable. The highest and lowest numbers are subtracted from each other, the result is the total capacitive skew in that cable sample. Cables with the lowest skew represent the best transmission lines.

Typical test results relationship of a 25 conductor 20ft cable when tested wires sorted by decreasing capacitance.

C pf/20ft	PD ns/20ft	Impedance in ohms
469.6	32.12	68.3
466.8	32.10	68.7
467.0	32.10	68.7
466.6	32.10	68.7
466.2	32.10	68.8
465.8	32.10	68.8
465.0	32.09	68.9
464.6	32.09	69.0
458.6	32.07	69.9
458.0	32.07	70.0
456.4	32.06	70.2
450.4	32.04	71.1
446.8	32.02	71.6
385.4	31.78	82.4
381.6	31.76	83.1
379.0	31.75	83.7
379.0	31.75	83.7
378.6	31.75	83.8
376.4	31.74	84.2
374.2	31.73	84.7
373.2	31.73	84.9
373.2	31.73	84.9
368.4	31.71	86.0
364.2	31.69	86.9
363.6	31.69	87.1

Impedance measurement

Test philosophy

Transmission line cable impedance is one of the most miss understood cable parameters. The characteristic impedance of a cable is nothing more than the value of a resistor placed at the end of a transmission line such that neither positive or negative reflections of energy go back to the source. If an end termination resistor is adjusted such that the input of the cable sees neither a positive or negative reflection (see page 20) Then the value of that resistor will be equal to the impedance of the cable.

Using an end termination resistor and a digital pulse signal generator is the most accurate way to determine the impedance of a cable sample. The end termination method of determining impedance most closely matches what happens in the real world, when the cable is used for digital data transmission.

If PD and capacitance of a cable sample have been accurately measured, then impedance may simply be calculated by using the following formula.

$$\boxed{IMPEDANCE\ (\Omega)\ -\ \frac{\left[\begin{array}{c} PROPAGATION \\ DELAY\ (nS) \end{array}\right] \times 999}{CAPACITANCE\ (pF)}}$$

You are guaranteed that the calculated value of impedance will closely match the impedance derived from the end termination method. This may not be the case if you attempt to measure cable impedance with a TDR or complex impedance analyzer using the open short method.

One advantage of the calculated impedance method is that you are deriving the <u>average</u> value of impedance, on the 20 ft test cable. Impedance, PD, capacitance and inductance will always follow the straight line impedance nomograph on page 21 if the individual tests are performed accurately and correctly.

Impedance measurement

Equipment used

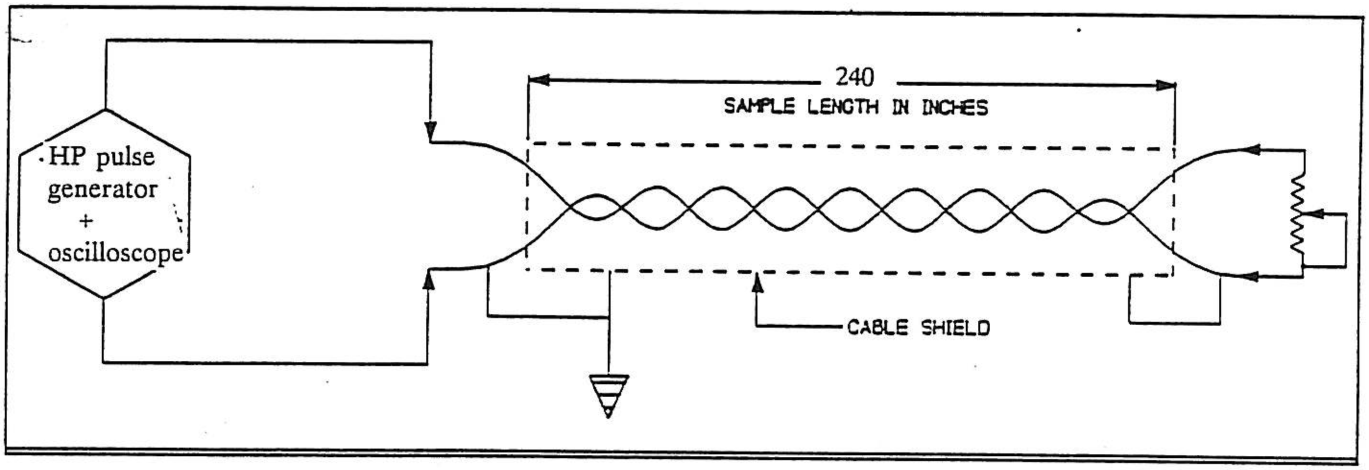
Calculated method: None, only capacitance and PD need be known.

End termination method: HP pulse generator or equal, wide band oscilloscope and a miniature adjustable non-inductive termination resistor.

TDR method: Standard TDR equipment. This method not recommended since even digital readout TDR's supposedly reading to .01 ohm accuracy can be off by as much as 6 to 8 ohms.

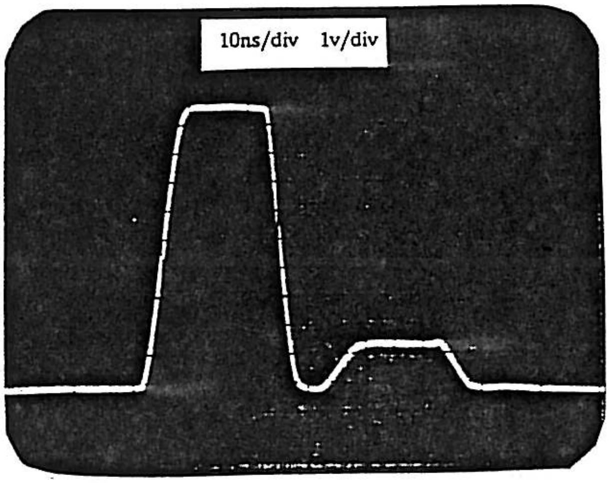
Test procedure (end termination method)

Setup should be as per this layout.

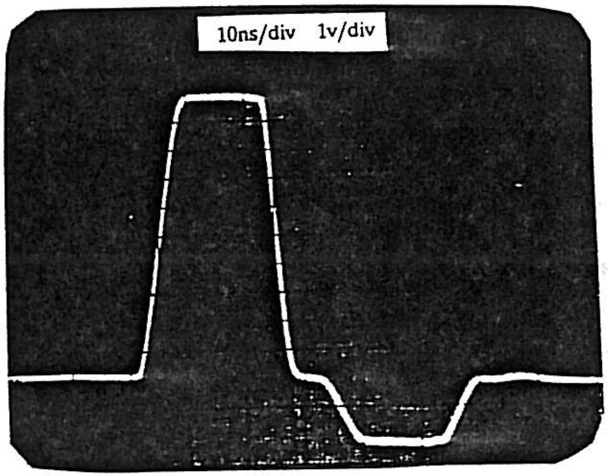


Pulse generator is set to handy values, typically a pulse signal of 5v, 40ns wide, 8 to 10 ns rise time and a repetition rate of 1 MHz. The end termination resistor is adjusted until there is neither a positive or negative reflection. The resistor is then removed and its value measured on an ohm meter. This measured value is the value that best matches the impedance of the test cable, in the real world of digital data transmission.

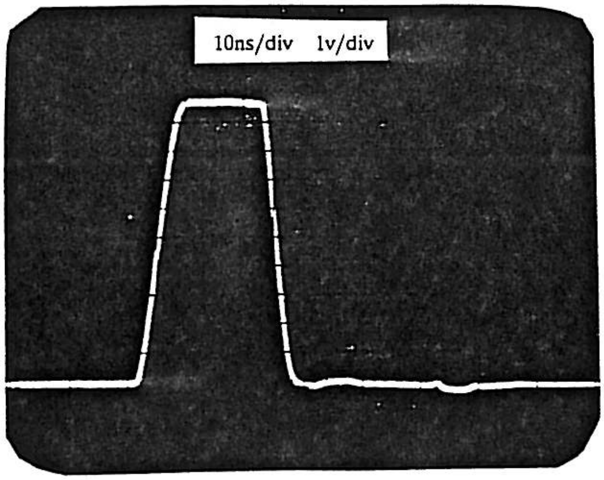
Impedance end termination scope pictures



End termination resistor adjusted higher than impedance of cable

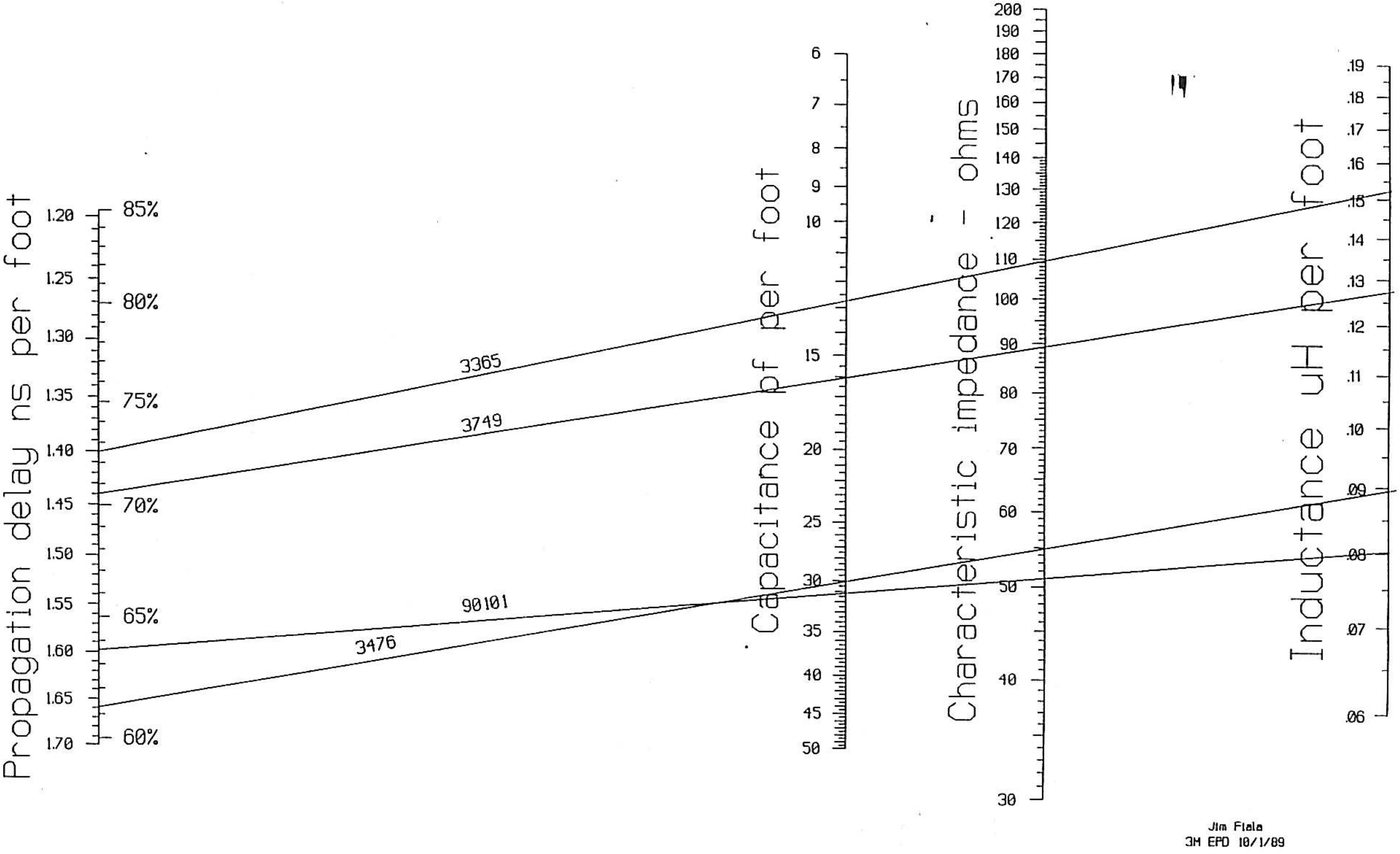


End termination resistor adjusted lower than impedance of cable



End termination resistance exactly matches impedance of the cable

Transmission-line impedance nomograph



Jim Fiala
3M EPD 10/1/89

IMPEDANCE NOMOGRAPH

The Impedance Nomograph follows classical transmission line electrical formulas. Every cable when tested in the proper configuration with accurate test methods will be a straight line on the Nomograph. If you know any 2 values the other 2 must fall on a straight line. This includes open line, flat cable, twisted pair, shielded or unshielded, balanced (differential) or unbalanced (single ended), twist and flat, etc.

All the electrical formulas are based on the effective velocity (speed) of the electrical signal traveling down a cable. This speed is determined by the effective dielectric constant of the insulator and characteristics of the wire. Here are some of the formulas and derivatives.

$$\underset{(\text{OHMS})}{\text{IMPEDANCE}} = \sqrt{\frac{L}{C}}$$

$$\underset{(\text{OHMS})}{\text{IMPEDANCE}} = \frac{999 \cdot \text{PD}\,(\text{NS/FT})}{\text{CAPACITANCE}\,(\text{PF/FT})}$$

$$\underset{(\text{uh})}{\text{INDUCTANCE}} = \underset{(\text{OHMS})}{\text{IMPEDANCE}^2} \cdot \underset{(\text{UF/FT})}{\text{CAPACITANCE}}$$

$$(E_R)\ \text{EFFECTIVE DIELECTRIC CONSTANT} = (0.983 \cdot \underset{(\text{NS/FT})}{\text{PD}})^2$$

$$\text{VELOCITY} = \frac{1}{\sqrt{\frac{L}{C}}} = \frac{C}{\sqrt{\underset{(\text{EFFECTIVE})}{E_R}}}$$

A check of most manufacturers catalogs show a deviation from a straight line on the Nomograph when catalog values charted. The problem is how cable values are measured. For instance propagation delay has typically been measured with a TDR (time domain reflectometer). This is a very poor instrument for accurately measuring PD. Scaling factors, operator interpretation, rise time degradation, and frequency scattering combine to produce an error of at least plus or minus 1 ns (nano second) over a 10 foot sample length. The corresponding impedance deviation error would be over 10 ohms. There are far better methods for measuring PD with an accuracy and repeatability of at least 25 pico seconds (.025 nano seconds) over 10 feet. This equates to about .2 ohm impedance deviation.

Inductance measurement

There is no need to attempt measurement of the cable inductance. The inductance may be calculated using the following formula or read from the impedance nomograph on page 21.

$$\boxed{INDUCTANCE\ (\mu H) = \frac{IMPEDANCE\ (\Omega)^2 \times CAPACITANCE\ (pF)}{1{,}000{,}000}}$$

For purposes of SCSI III and testing of 20 ft cable samples, I recommend the following values.

Rise time degradation
< 1 ns/20 ft

Square wave voltage attenuation
<.75 v/20 ft

Propagation delay
< 1.65 ns/ft, 33 ns/20 ft

Propagation skew
< 1.5 ns differential/20 ft

Capacitance
< 25 pf/ft, 500 pf/20 ft

Capacitive skew
< 100 pf/20 ft

Impedance
> 80 ohms