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X3T9.2/91-002R1

Date: 15 Feb 91
From: Kurt Chan, Hewlett-Packard
To: X3T9.2 Membership
Subject: Effects of cable attenuation on optimal cable impedance

In X3T9.2/90-185, Bill Spence (Texas Instruments) makes some observations regarding 20+ meter single-ended bus configurations which warrant further analysis. The following paper provides an explanation for the empirical data gathered by Bill. Revision 1 addresses noise margin balancing for 6m systems as well as 25m systems.

First, an analysis of lossless lines will be performed, followed by an analysis of lines with varying degrees of attenuation, ending with a summary of how impedance cable length, and attenuation affect voltage margins.

ANALYSIS OF LOSSLESS LINES:

The two most commonly used analytical tools used in the study of terminated transmission line systems are the SPICE simulation language and the Bergeron diagram. If we analyze the behavior of lossless SCSI cables using these tools, they will give us a starting point for predicting how a system with non-ideal components should behave.

Figure 1 depicts the Bergeron diagram for the asserting edge of a SCSI signal on a 70 ohm cable with a worst-case source (.048V@.048A):

The Bergeron diagram provides an intuitive tool for analyzing transmission line systems with both linear and non-linear termination elements, and is based upon the knowledge that a voltage wave at any point on a transmission line is governed by the following equation:

$$V = I * Z_0$$

Although a mathematical model can be constructed from the principles of the diagram, the accuracy of the solution is generally proportional to the accuracy of one's drawing tools. The rules for construction are as follows:

1. The Y axis represents the voltage on the transmission line. The X axis represents the current. In order to make a graphical solution easy, the X axis is normalized to the characteristic impedance of the cable under analysis, so that all forward and backward waves have a slope of +1 and -1, respectively.

2. Construct the far termination load line using the open-circuit voltage as the Y-intercept. The slope of the line is the termination resistance normalized to the characteristic impedance (Rterm/Z0 = 110/70).

3. Construct the source load line in the asserted state (low). The Y-intercept is the on-state Thevenin voltage:

$$2.85 * \frac{R_{on}}{R_{on}+R_{term}} = 0.2375V$$

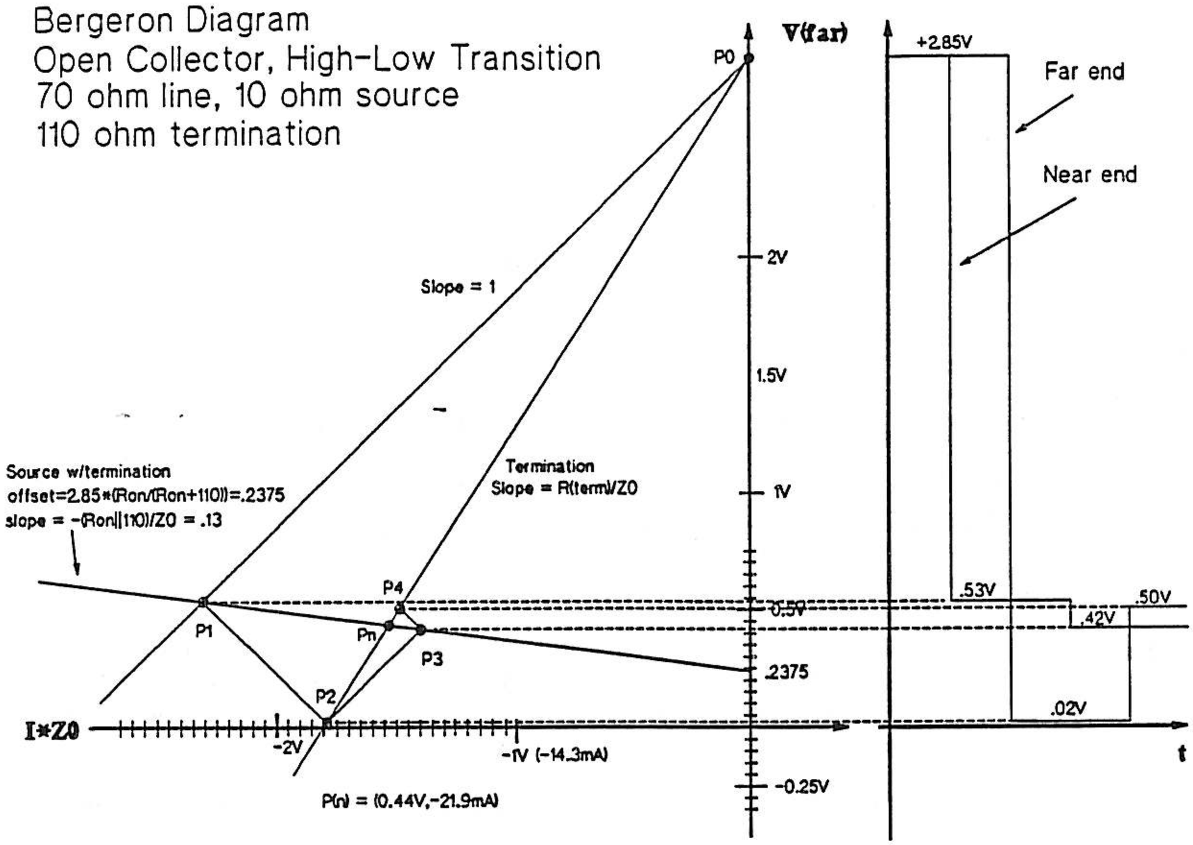


Figure 1 - Bergeron Diagram for Lossless 70 ohm Cable with Alt-2 Termination

and the slope is the on-state Thevenin resistance normalized to Z0:

$$Slope = -\frac{R_{on} \,||\, R_{term}}{Z_0} = 0.13$$

4. Project a line beginning from the open-circuit voltage (P0) with a slope of +1. This is the initial forward wave.

5. At the intersection with the far termination load line (P1), project a line with slope -1. This represents the first reflection back towards the source.

6. Repeating this procedure creates the "Bergeron snail" which converges on the quiescent point V(ol), which is strictly a function of the source and termination DC load lines.

Below is the same diagram for a 90 ohm line instead of 70:

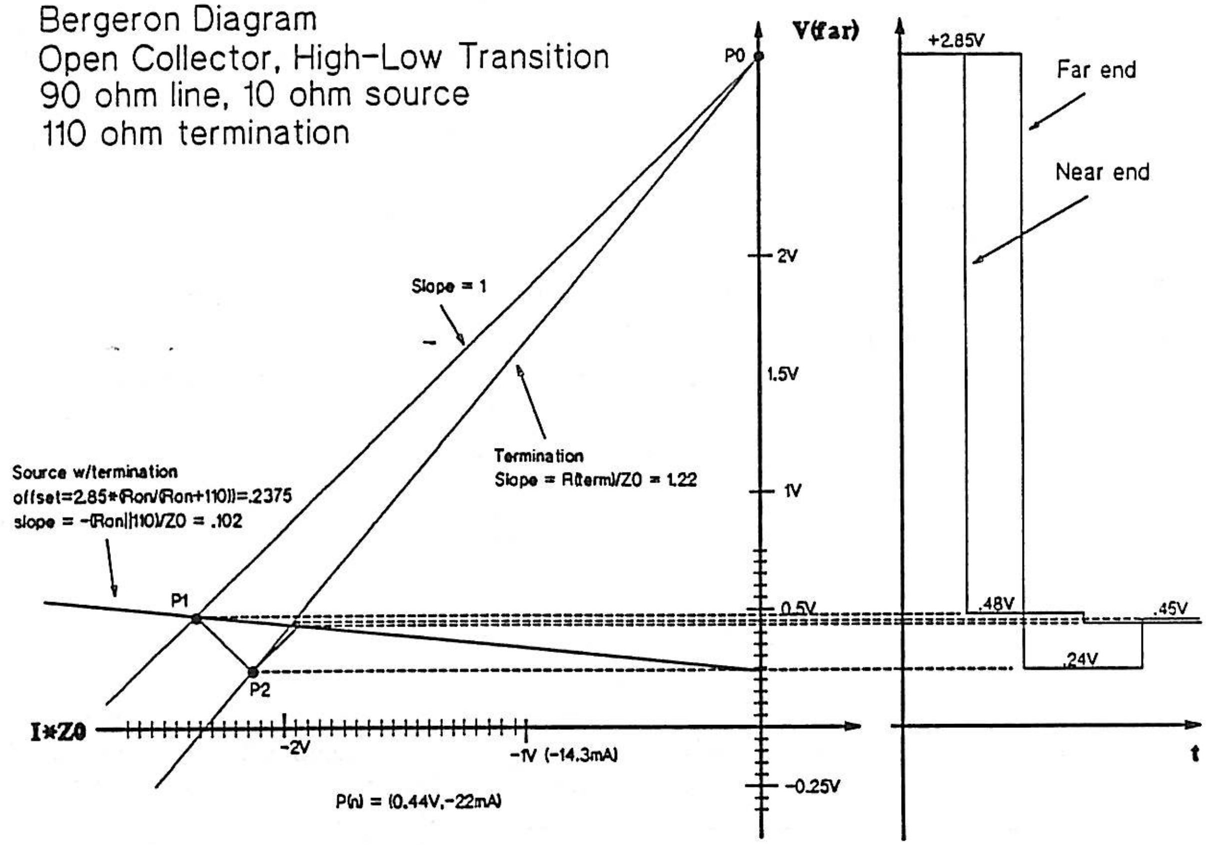


Figure 2 - Bergeron Diagram for Lossless 90 ohm Cable with Alt-2 Termination

The SPICE plots shown on the next page confirm the results of the Bergeron diagrams, with the far end pulling down to about .25V for 90 ohms and nearly 0V for 70 ohms. Also note that both tools agree that for the NEAR end, the higher-impedance cable pulls down better than the lower-impedance cable. This initial voltage is simply the result of a voltage divider effect between Z0 in parallel with the near pullup, and the pulldown resistance:

$$V_1 = V_{term} * \frac{R_{on}}{R_{on} + (R_{term} || Z_0)}$$

which comes out to 0.54V for 70 ohms, and 0.48V for 90 ohms.

Also note that regarding the initial high-low assertion step on lossless lines from 70-90 ohms:

- At the NEAR end, the step is of LOWER magnitude for LOWER impedance cables.
- At the FAR end, the step is of LOWER magnitude for HIGHER impedance cables.

Very low impedance cables will result in undershoot at the far end, while attenuating BOTH the initial asserting and deasserting steps at the near end. Higher impedance cables will tend not to undershoot at the far end.

On lossless lines, regardless of the magnitude of the initial steps, the waveforms always eventually converge on the same quiescent point. As the cable impedance approaches the termination resistance, the number of converging steps approaches one. This can be visualized graphically on the Bergeron diagram: as the slope of the termination load line approaches unity (Rterm=Z0), the number of far end reflections goes to zero since the quiescent point is equal to P1.

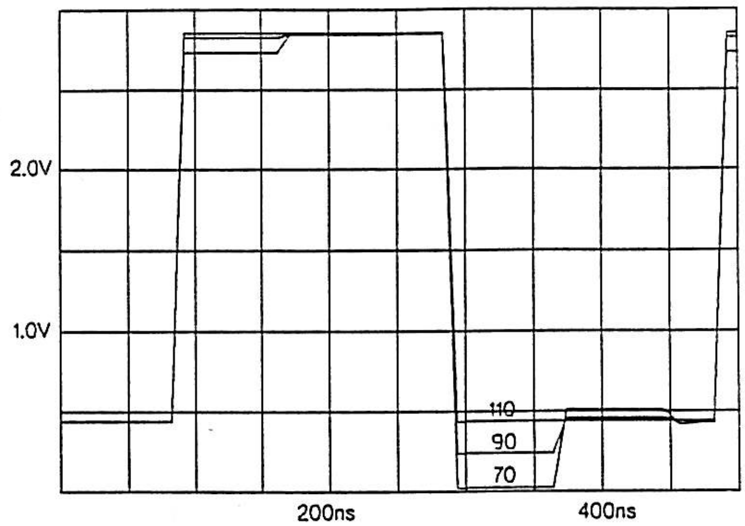


Figure 3 - SPICE Plot of Lossless Cables, Far End

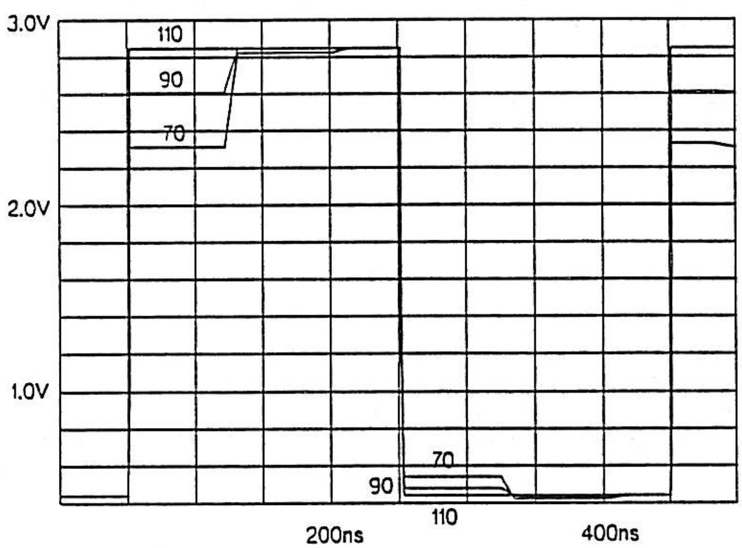


Figure 4 - SPICE Plot of Lossless Cables, Near End

A "perfect" zero-ohm source represented by a horizontal load line on the Bergeron diagram will pull the near end voltage to zero. On lossless cables which are mismatched with R(term) > Z0 this will always result in some undershoot; the amount depending on the degree of mismatch between R(term) and Z0.

The reason the waveforms in Figures 1-4 do not exhibit this undershoot is due to the nonzero pulldown resistance modelled in the SCSI drivers.

ANALYSIS OF LOSSY LINES:

When attenuation is considered, the picture changes dramatically. The concept of attenuation is simple: if a voltage is applied to the input of a device, the attenuation of the device is proportional to the voltage level at its output. This relationship is commonly expressed in decibels:

$$Attenuation[dB] = \log_{10}(\frac{V_2}{V_1})$$

The SPICE program models attenuation for a transmission line as follows:

$$A = Attenuation\ Factor = ATTN[dB/cm] * NVEL * c * t(d)$$

where:

ATTN is the cable attenuation spec in Db/cm
NVEL is the velocity of light through the cable
c is the velocity of light through a vacuum (2.99793e10 cm/s)
t(d) is the cable delay (indirectly specifies the cable length)

The attenuation factor describes the logarithmic relationship between the entry and exit voltages on a cable of known velocity and length:

$$A = 20 \log (\frac{V_{entry}}{V_{exit}})$$

$$\frac{A}{20} = \log (\frac{V_{entry}}{V_{exit}})$$

$$10^{\frac{A}{20}} = \frac{V_{entry}}{V_{exit}}$$

Physically, attenuation is caused by both conductor losses (which are modeled as series resistance) and dielectric losses (which are modeled as shunt resistance). An examination of 11 different SCSI cable data sheets revealed that real-life attenuation measurements vary with the frequency of the applied voltage, and whether the measurements were single-ended or differential. However, the following analysis is independent of these measurement differences. The average SCSI cable had a single-ended attenuation of about 6 dB/100' (measured somewhere between 5 and 50MHz), or about twice the recommended Fast SCSI specification.

Figure 5 shows the relationship between cable attenuation and the entry voltage needed to produce an exit voltage of 2.0V when applied to 6m and 25m cables terminated in their characteristic impedance. The percentages represent the % attenuation for the specified length of cable. [redacted]

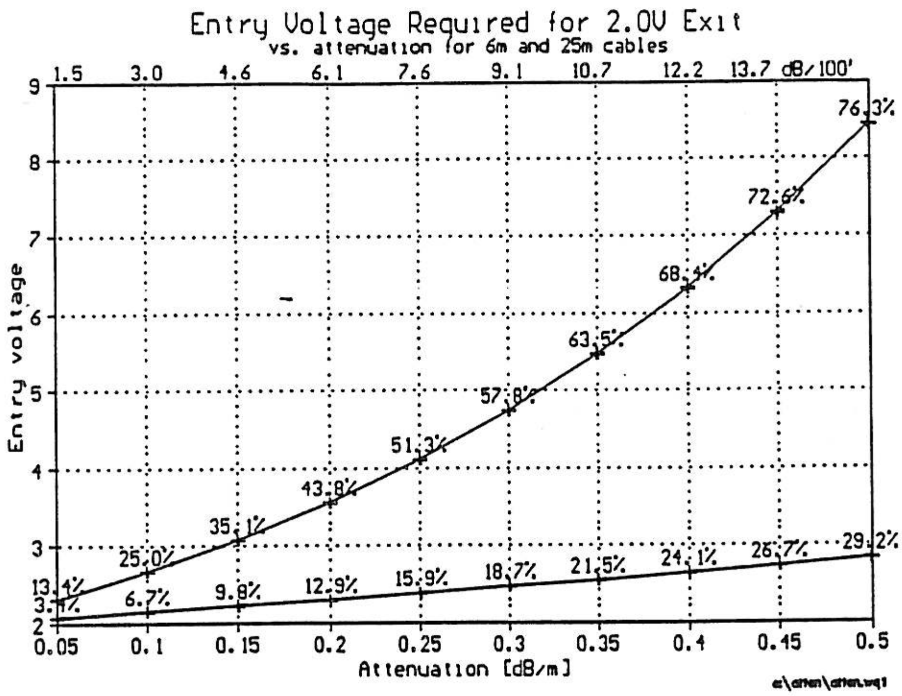


Figure 5 - Comparison of 25m and 6m Attenuation

Note that a cable that attenuates a signal by only 19% in 6m lengths will attenuate the same signal by 58% in 25m lengths.

The SPICE plots below demonstrate the attenuation predicted by the previous graphs. At the far end, both the asserting and deasserting levels are attenuated, so that both the 2.0V and 0.8V thresholds are jeopardized.

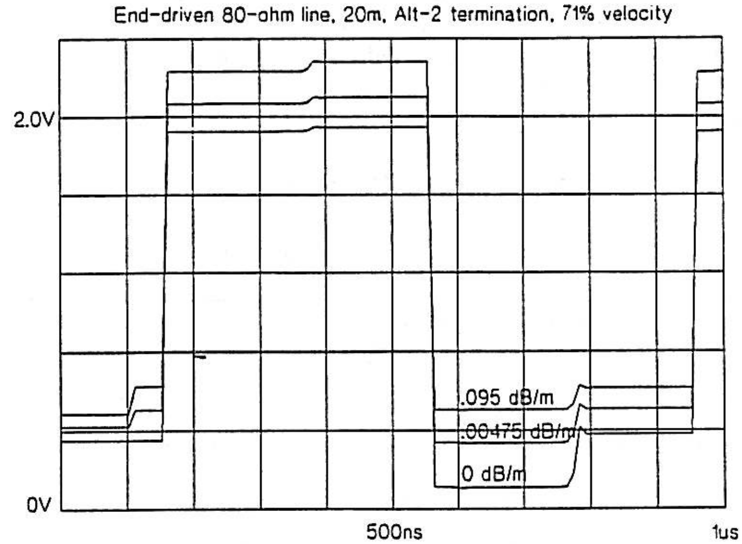


Figure 6 - Far end, 20m cable, nonzero attenuation

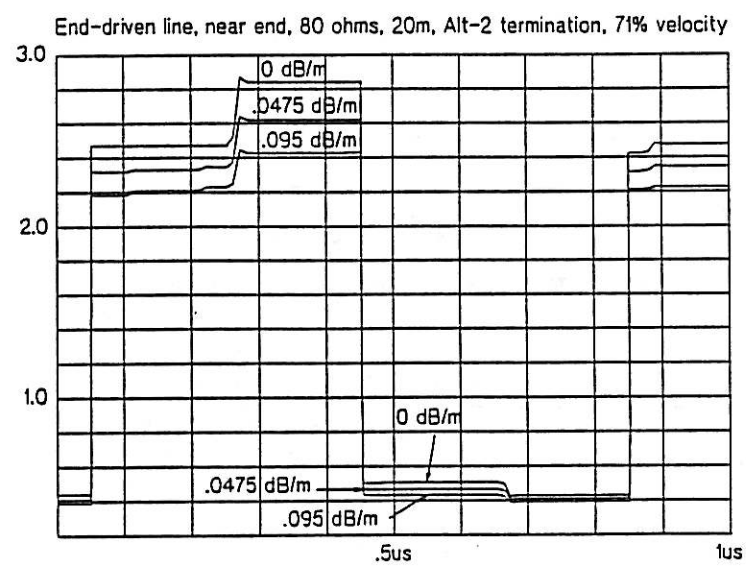


Figure 7 - Near end, 20m cable, nonzero attenuation

PUTTING IT ALL TOGETHER

The numbers graphed below taken from SPICE simulations give us a means of weighing tradeoffs between high and low impedance cables. Figure 9 shows how much low level margin we have for various combinations of impedance and attenuation. Note that the **higher** impedance cables provide the **LEAST** amount of margin on the falling edge. Figure 10 shows the amplitude of the first rising step at the near end of the same cables. Note that the **higher** impedance cables provide the **MOST** amount of margin. Note the 0.8 and 2.0V levels!

Figure 9 - Low Noise Margin as a Function of Impedance and Attenuation

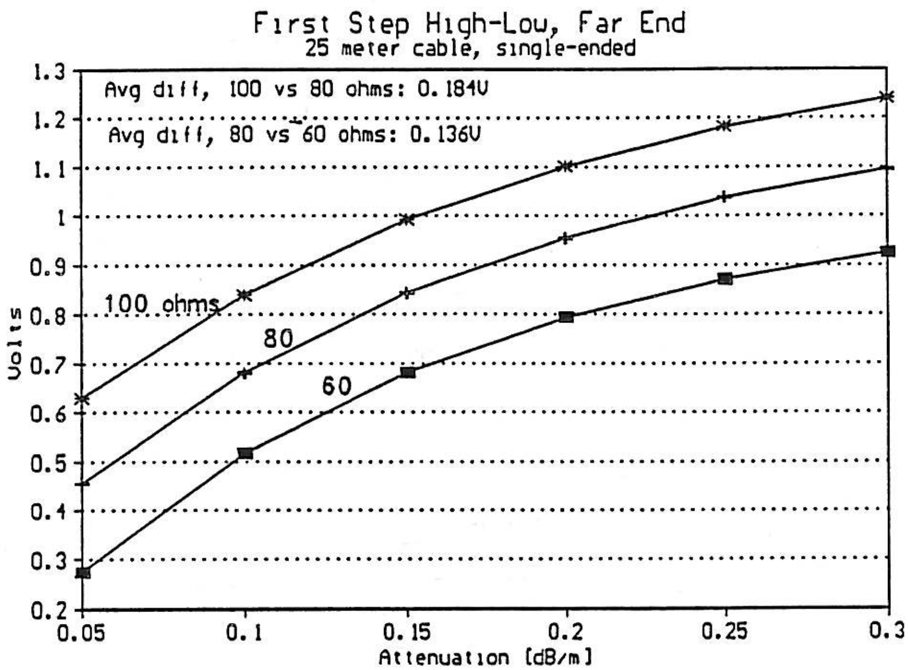
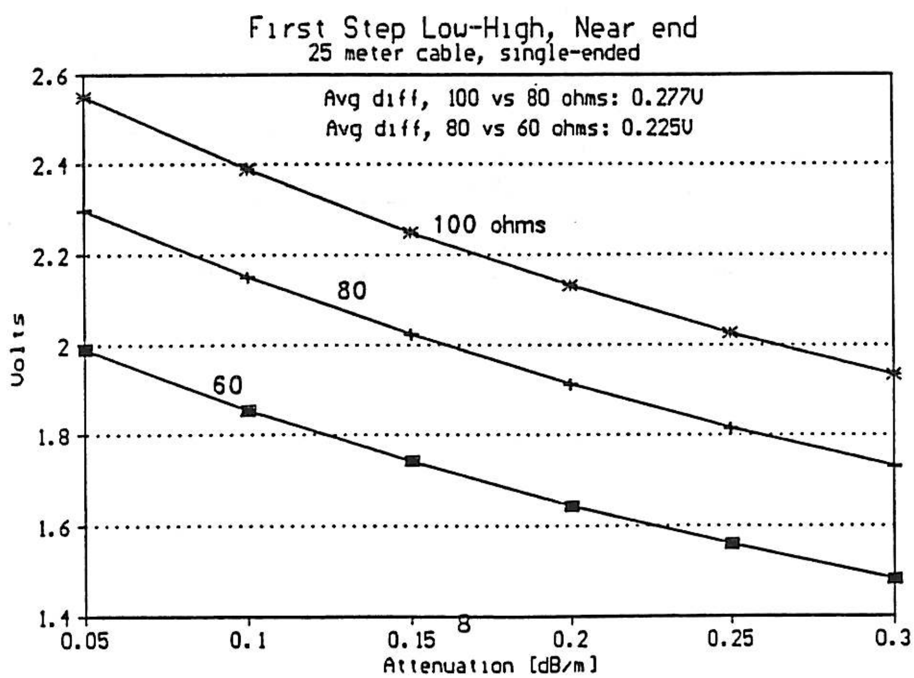


Figure 10 - High Noise Margin as a Function of Impedance and Attenuation



CONCLUSIONS

1. SCSI cables must perform a balancing act if equal amounts of low and high noise margin are to be achieved. Interestingly enough, Bill Spence's conclusion that cables in the 78-82 ohm range are best balanced for single-ended operation at 20+ meter lengths is confirmed by these analytical models. I've performed further simulations to determine what the optimal impedance for various cable/terminator combinations:

Cable Impedances for Balanced Noise Margins

Configuration	Impedance @ 0.1dB/m attenuation	Margin
25 meter, Alt-2	79 ohms	.13V
6 meter, Alt-2	85 ohms	.45V
6 meter, Alt-1, max TERMPWR	93 ohms	.58V
6 meter, Alt-1, typ TERMPWR	106 ohms	.49V
6 meter, Alt-1, min TERMPWR	118 ohms	.44V

Note that the ideal impedance varies as a function of cable length and termination. These margins and impedances will also change when cables with different attenuation or lower-voltage drivers are considered.

2. Rising edge margins are much more sensitive to impedance changes than falling edge margins. Figures 9 and 10 show that a 20 ohm change in impedance affects rising edge margins by about .25V compared to only about .15V for falling edge margins.

3. Special care to attenuation must be taken when using single-ended at distances beyond the 6m SCSI-2 limit.

4. Systems with Alt-2 termination need cables which are much higher in impedance compared to Alt-1 termination.

5. Lower attenuation is universally better. The .095dB/m spec for Fast SCSI cables should apply to ALL SCSI cables unless there is an overriding technical reason why this isn't feasible.

6. Care should be taken in extending the lengths of 30AWG cables (particularly beyond 6m) due to attenuation concerns.

7. A common attenuation measurement method should be agreed upon.