Keywords: cable loss, automatic test equipment, ATE, parametric measurement unit, PMU, pin electronics, PE, cable compensation, drive-compare-load, DCL, dielectric loss, skin effect, return path loss, connector, relay, high, low frequencies, copper, conductor

APPLICATION NOTE 4303

Impact of Cable Losses

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Abstract: There are many test companies that design, build, and ship large-pin-count automatic test equipment (ATE). These testers have complex integrated circuits that drive each pin of the tester. A tester could have as many as 4096 pins. ***Figure 1*** *shows that, at each pin, there is usually a driver, comparator, load, and sometimes even a parametric measurement unit (PMU). These electronics are attached to a cable, which is then connected to the pin. To keep costs down, a vendor may choose to use low-quality cables. All cables, especially low-quality ones, suffer from signal losses that reduce the ultimate performance of the tester.*

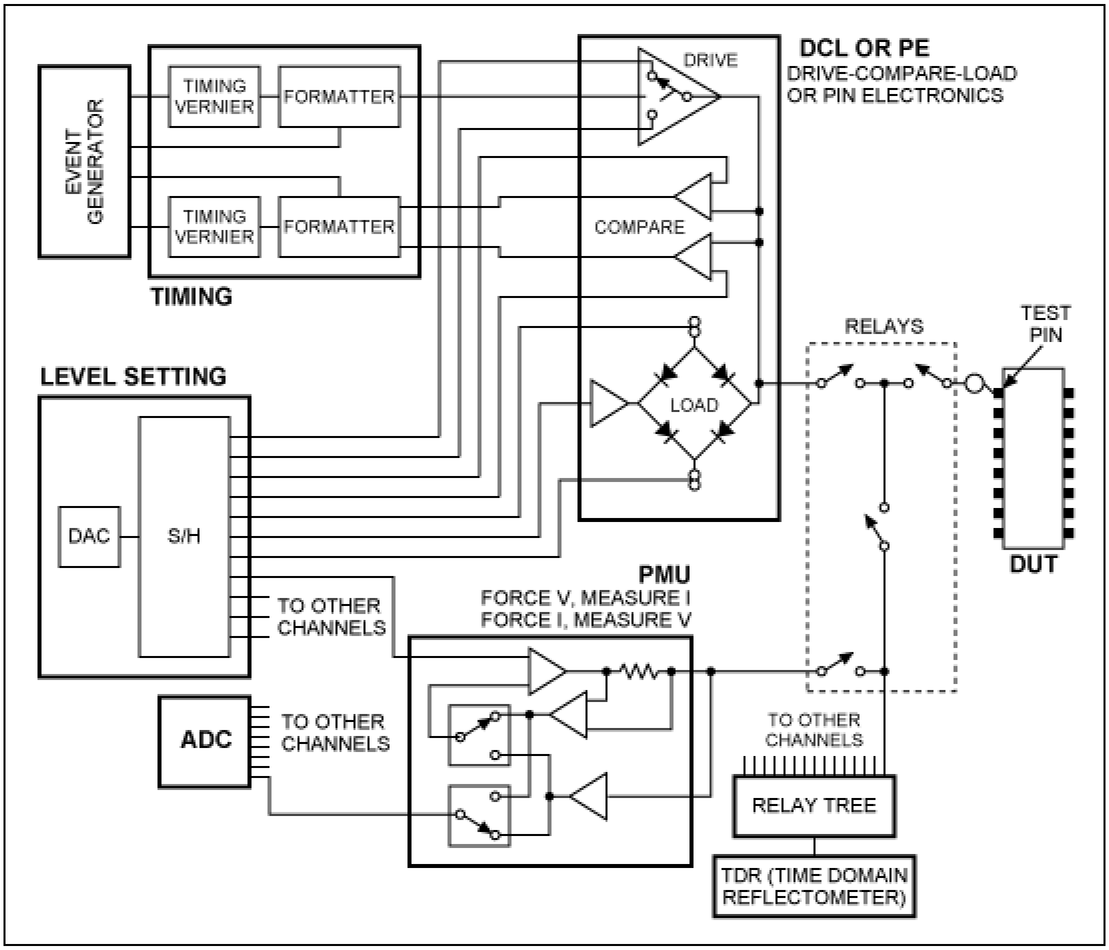

Figure 1. Typical tester setup for one device under test (DUT) pin.

Defining Cable Loss

In a typical coaxial cable (**Figure 2**), there are two main components of cable loss: skin-effect loss and dielectric loss.

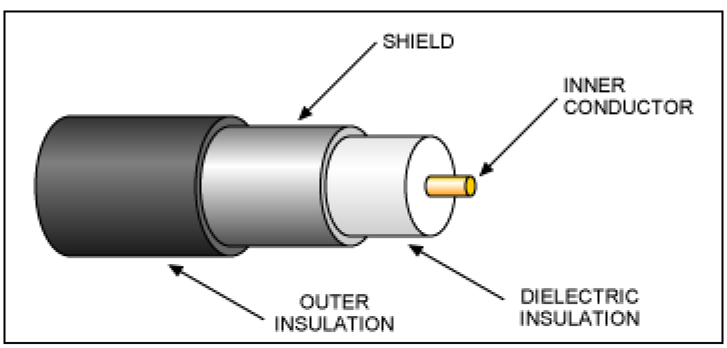

Figure 2. Typical coaxial cable.

Skin-Effect Loss

At high frequencies, the signal tends to propagate along the surface of the inner conductor (shown in

Figure 2). This is known as skin-effect loss. This skin depth (δ) is defined as:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

where ω is the frequency in rad/s, μ is the conductor's magnetic permeability in H/m, and ρ is the conductor's resistance in ohmmeters. The skin-effect loss causes the resistance per unit length, R_l, and the inductance per unit length, L_l, to increase with the square root of the frequency. The resistance per unit length is calculated as:

$$R_l = \frac{\rho}{w\delta} = \frac{1}{w}\sqrt{\frac{\omega\mu}{2\rho}}$$

where w is the width of the conductor. For a circular wire of radius r, the width is 2πr. The return path resistance also needs to be added, but it is normally much less then the forward path and can be ignored.

Dielectric Loss

The dielectric insulator, shown in Figure 2, also contributes to frequency-dependent cable losses. The dielectric constant (ε) is defined as:

$$\varepsilon = \varepsilon'(1 + j\varepsilon'') = \varepsilon'(1 + j\tan\delta)$$

where ε' is the real component of the dielectric constant, and tanδ represents the imaginary, or loss tangent, dissipation factor of the dielectric. Because the dielectric insulator affects capacitance, the capacitance per unit length (C_l) changes to $C_l(1 + j\tan\delta)$.

Total Cable Loss

Including skin-effect and dielectric losses, the ideal cable per unit length model can be changed to include these losses, as shown in **Figure 3**.

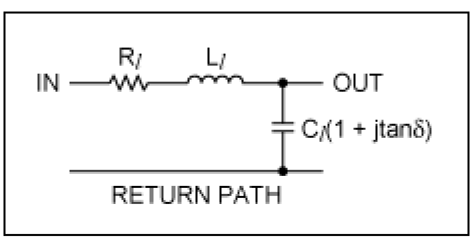

Figure 3. Simplified cable model.

From Figure 3, we define the propagation constant as $jk = \sqrt{ZK}$, where Z is the distributed series impedance, and Y is the distributed parallel admittance. In this case:

$$jk = \sqrt{(j\omega L_l + R_l)(j\omega C_l(1 + j\tan\delta))}$$

By using a Taylor expansion approximation and further simplifying, the following term can be extracted:

$$jk \approx j\omega\sqrt{L_l C_l} + \frac{1}{2Z_O\omega}\sqrt{\frac{\omega\mu\rho}{2}} + \frac{\omega\tan\delta\sqrt{\varepsilon_r}}{2c}$$

where Z_O is the line's characteristic impedance, ε_r is the relative dielectric constant, and c is the speed of light.

Finally, what we are really after is the cable gain, $H(f) = e^{-jkl}$, where l is the length of the line. Using the findings from above, we arrive at:

$$|H(f)| = e^{-\alpha 1\sqrt{f} - \alpha 2fe}$$

where:

$$\alpha 1 = \frac{1}{2Z_O\omega}\sqrt{\pi\mu\rho}$$

and

$$\alpha 2 = \frac{l\pi\tan\delta\sqrt{\varepsilon_r}}{c}$$

The simplistic conclusion that we want to see from the above calculations is:

1. Skin effect losses (α1) dominate at low frequencies (**Figure 4**)
2. Dielectric losses (α2) dominate at high frequencies (Figure 4)

In real cables, H(f) varies somewhat from the approximations above. However, it is accurate enough for most ATE work, where the attenuation increases by 6dB at the most.

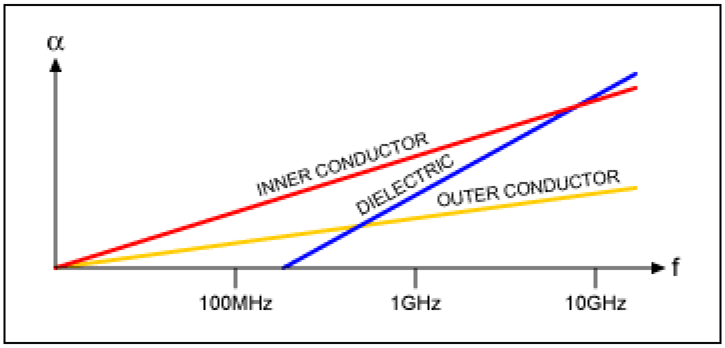

Figure 4. Representation of skin-effect (inner conductor), dielectric, and return-path (outer conductor) losses.

Figure 4 provides a basic representation of losses for the typical coaxial cable shown in Figure 2, which has a characteristic impedance of 50Ω, an inner copper conductor, and an outer conductor made of braided steel. Each cable will have its own unique losses, but will still show the same trend seen in Figure 4.

Summary of Cable Losses

It is not the intent of this application note to offer a rigorous mathematical approach to the derivations of cable losses—this can be obtained from various scholastic sources. However, what was demonstrated in the equations is summarized in Figure 4. From the above analysis we obtain the following important points:

1. All cables have losses, and these losses will ultimately limit the performance of a system. The amount of the loss depends on the quality of the cable and its specifications.

2. The losses that do occur are:

a. Skin-effect losses, which dominate at low frequencies
b. Dielectric losses, which dominate at high frequencies
c. Return-path losses, which are insignificant and can be ignored for most cases
d. Losses through connectors, relays, and other connections made to the output nodes or the DUT

Cable Loss vs. Cable Cost

Figure 5 shows the cable loss for typical cables, while **Table 1** compares the cost of some cables relative to their losses.

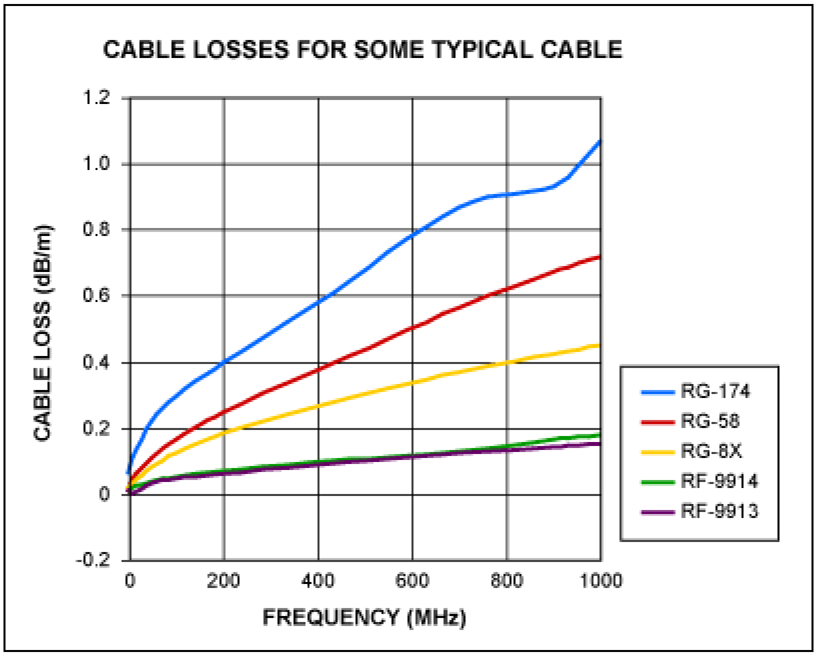

Figure 5. Cable losses for a variety of cables.

Table 1. Typical Cost per Foot for Various Flexible Coaxial Cables from One Selected Manufacturer

Cable	Loss at 900MHz (dB/m)	Cost per Meter ($)
RG174	0.75	1.3
RG142	0.382	14.6
RG400/U	0.3492	15.11
RG232/U	0.4589	10.4
R393/U	0.296	22.7
RG58 low loss	0.3691	1.46
RG58/U	0.531	1.14
RG8X	0.25	1.79
RG8	0.14	14.3

Notes

1. The cost multiplier of a good quality cable compared to that of a low-quality cable is as high as twenty to one (Figure 5, Table 1).
2. ATE manufacturers prefer low-cost cables, but may suffer system performance degradation that is related to such cables.
3. Pin electronics without cable compensation cannot correct for cable losses.
4. Substituting high-cost, very wideband, power-hungry pin drivers only provides marginal improvements over lower cost, lower bandwidth, lower powered pin drivers when using lossy cables.
5. Using 4096 cables in a single tester means that, for each meter in length, the cost of the cable assembly could run from $5325 to $92,979 (Table 1).
6. By transferring cable compensation to the pin electronics, the savings on the 4096 pin tester examples could possibly be as high as $92,979 - $5325, or $87,654, per tester.
7. The cost values in these notes are based on the information in Table 1, and could vary significantly depending on the ATE manufacturer. However, these numbers highlight the large cost associated with the cable assemblies and, therefore, why it is important for ATE manufacturers to find alternative solutions that allow the use of lower cost cables.
8. The cables listed in Table 1 are flexible cables. The best cables are the semirigid and rigid cables. These cables cost approximately $30 per foot, which is a factor of 3 or more over the best of the flexible cables. These would be cost prohibitive to any tester manufacturer, and hence are not used.
9. As tester frequencies increase, the need for cable compensation becomes imperative. High-end testers are already approaching speeds of > 1Gbps.

Performance Degradations Due to Cable Loss

For testers that run in the 200Mbps range, cable loss may not be a big concern. However, for testers running at 500Mbps and higher, the performance of the full signal path, electronics, cable, and pin must be analyzed very carefully to ensure that full performance is measured correctly at the pin. The following performance specifications are the most important for a high-speed tester:

1. DC accuracy of the waveform levels
2. Rise and fall times
3. Maximum toggle rate
4. Minimum pulse-width capability
5. Propagation accuracy and matching relative to each edge
6. Propagation skews, such as propagation vs. minimum pulse width, amplitude, and common mode

All of the aforementioned performance characteristics are impacted by the choice of the cable. As the toggle rates increase, cable losses begin to dominate and limit the performance of the tester, regardless of the driver's bandwidth for driving the cable. The plots in **Figures 6** and **7** represent and highlight these problems.

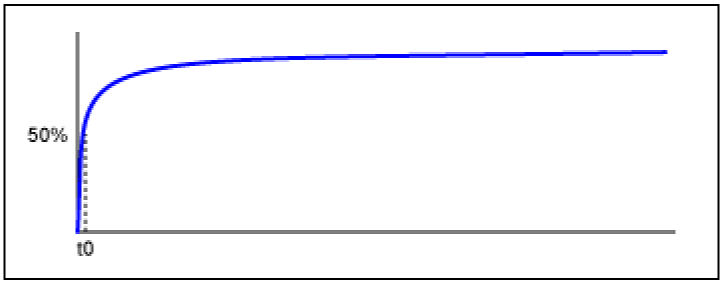

Figure 6. Step response of short/high-quality cable.

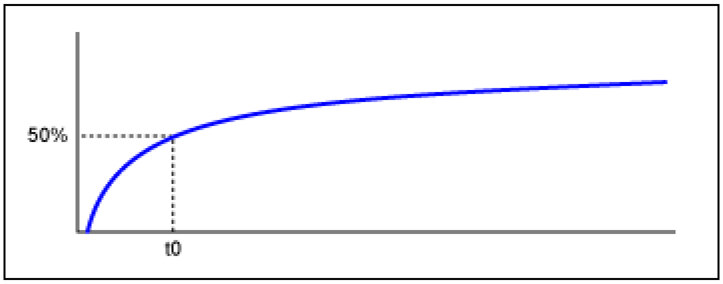

Figure 7. Step response of longer/low-quality cable.

Figures 6 and 7 illustrate waveforms that most engineers have already seen and know about. However, the following is noteworthy:

1. t0 represents 50% of the waveform's amplitude. As a rule of thumb, the 10% to 90% rise time is about 28.6 x t0. These two waveforms show a significant degradation in the rise times for these two cable lengths.
2. The bandwidth-limiting rolloff nature of the curve impacts the maximum toggle rate, minimum pulse widths, and bandwidth. So, the degradation in the signal path is obvious from these plots.
3. The signal degradation has nothing to do with the actual driver. In this case, we are feeding a step response of infinite bandwidth, and it is the cable that is creating the slowdowns in rise times.
4. For higher speeds and longer cables, this problem gets worse.
5. All cables, no matter what length or quality, display the characteristics in Figures 6 and 7 to some degree.
6. It is imperative to find a solution for cable losses so as to allow the full bandwidth of the driver, otherwise the increase in cost for higher quality cables adds little to no value to the application.
7. Designing cable compensation into the electronics solves these cable loss issues.

Conclusion

Cables used in a high-speed tester can impact the overall performance of the tester and will ultimately limit its performance. Due to the high cost that can be associated with these cables, low-cost cables, which have high losses, are normally used in these high-speed systems. As the speeds of these testers approach 1Gbps and higher, you can no longer ignore these losses. Replacing the drivers with higher bandwidth drivers does not compensate the loss caused by these cables, and hence the cables will limit the performance of the system.

It is necessary to find a solution to these cable losses to allow testers with bandwidths greater than 1Gbps to perform at their full potential. Fortunately, there is a solution, and that is to design cable compensation into the electronics.

Related Parts		
MAX9957	Fast Dual Driver for ATE with Waveform Shaping	Free Samples
MAX9959	25V Span, 800mA Device Power Supply (DPS)	
MAX9979	Dual 1.1Gbps Pin Electronics with Integrated PMU and Level-Setting DACs	Free Samples

More Information

Application Note 4303: http://www.maximintegrated.com/an4303
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