White Paper

Automating Test

Within Manufacturing Processes

pickering

CONTENTS

When tested on a bench, a product generally has the optimal test environment, with short and direct connections to the stimulus and measurement devices. But in production, the interface between a device under test (DUT) and the test instruments will likely include a network of cabling, a signal distribution or switching subsystem, a connector panel, and device-specific adapters. All of these components do nothing to enhance the pristine signals that were—during product development—passed back and forth directly between the instruments and product on the bench. Instead, they contribute opportunities for signal degradation. In essence, all of the cabling, interfacing and switching should now be considered as an extension of the test instrument and must be allowed for when assessing the instrument's capabilities. This white paper will explore the issues in more depth, focusing on how path resistance, line capacitance and insertion loss affect test results and what can be done to minimize their impact.

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1. Objectives of a successful automated test system

As a new product concept makes its way through research and development, validating the design is often a manual process completed on a lab bench. Once the product design has been validated, product acceptance requirements are transitioned to the production test engineering team. Ideally, the product will have been designed with testability in mind, but quite often, production testing is an afterthought. The test engineering team then has the responsibility to create an acceptance test procedure that is part of the manufacturing process, and which is efficient enough to support production demand. This procedure is frequently automated to help accelerate test times and reduce errors typically associated with manual interventions by test technicians. Application code running on a PC controls test instruments in a rack that are supplying stimulus to and measuring the response from the product being tested. The challenge of creating an automated test platform is often increased when the platform is required to be versatile enough to test multiple types of products. Product specific test adapters that are used to route system I/O to the device being tested introduce multiple transition points that can corrupt the integrity of test signals.

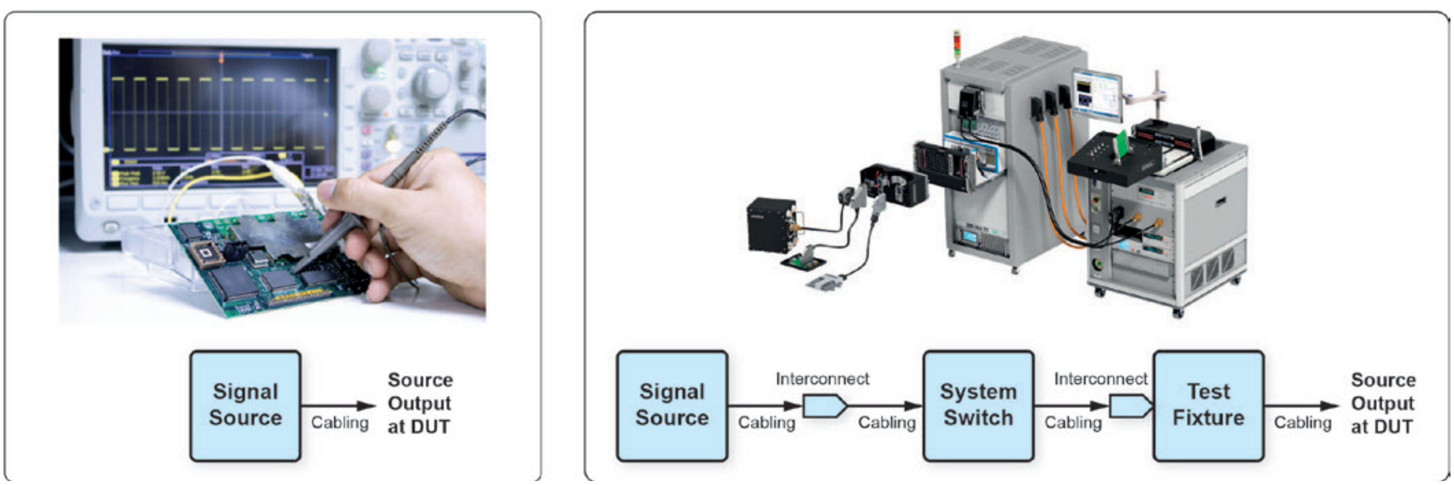


Figure 1 - Making the connection in an ATE system

* Image courtesy of Virginia Panel Corporation.

1.1. Glossary of terms used

A short glossary of terms that will be used for those unfamiliar with them:

- **PXI** – Open industry standard for a modular test instrumentation and switching platform based on PCI/PCIe
- **Receiver** – Mass termination panel that provides the connector interface between the test article and test instrumentation
- **Signal Routing System** – Everything residing in the path between test instrumentation and the test article, including switching components and any external connectors and cabling

2. Journey of a test signal

Figure 2 shows a dual channel function generator, which is connected to multiple points on a device under test (DUT). A small switching subsystem is used to distribute the outputs of the generator. The I/O of the switches and the Instrument is wired to a common receiver panel and then connected in an adapter that is specific to the device being tested. Finally, this adapter is wired to the DUT.

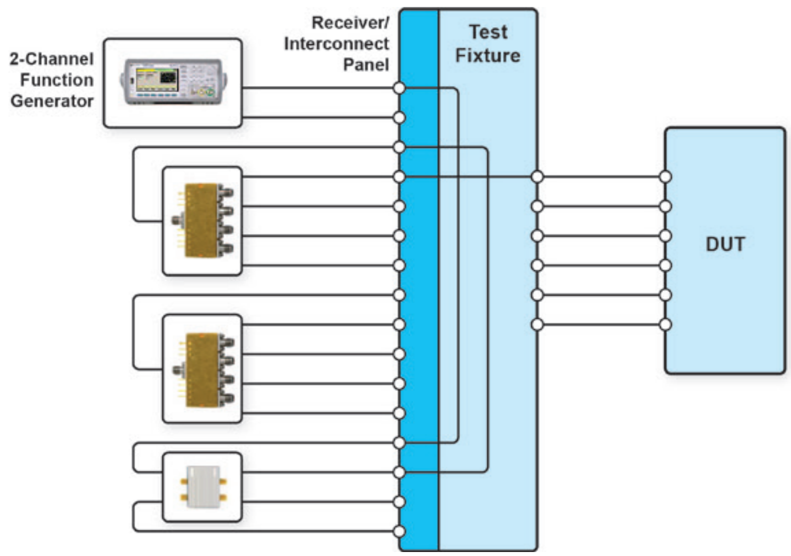


Figure 2 – Output of a function generator and its path to the DUT

The path that the signal follows introduces multiple attack points on the integrity of the signal. Let's say in this example; the DUT requires an input pulse with a minimum width and rise/fall time to initiate a sequence of events. In this simple example, a the pulse generated by the function generator first travels through a few feet of cabling to the test interface, a connection point and more cabling through the test fixture, back to the first layer of the switch, back through the interface and fixture to the second layer of the switch and finally out to the DUT. In essence, the 10+ feet of cabling, connectors and switch contact points have become part of the function generator.

The cabling, switch contacts and connectors in the signal path do nothing to improve signal integrity. Instead, they are working against it. The impact on the signal is not always easy to calculate or predict, especially when there are multiple possible paths designed into the system. The result is uncertainty in the integrity of the signal, the resulting measurements and, ultimately, uncertainty in the quality of the product. So while the function generator is likely performing to its stated specifications, once in a test system, its output once through the signal routing system may end up suggesting otherwise.

3. Roadblocks

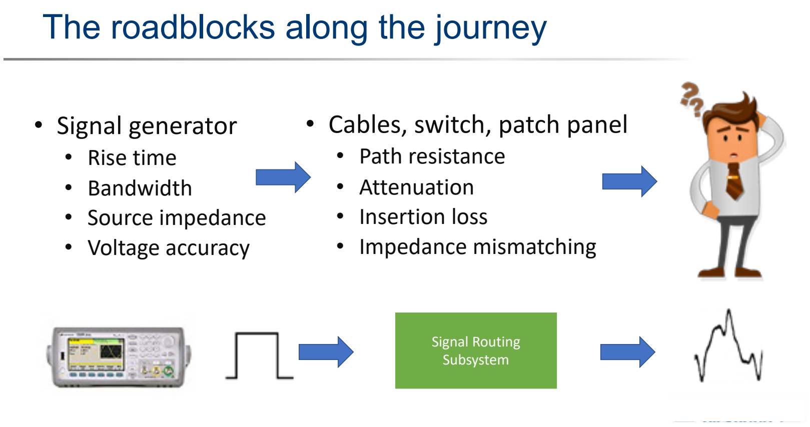


Figure 3: What goes into the signal routing system is not necessarily what comes out

In such a system, the function generator will be specified for several specific characteristics, such as rise time, bandwidth, source impedance and amplitude accuracy. The signal routing system contributes capacitance, path resistance, insertion loss, reflected power, and various opportunities for impedance mismatching and signal attenuation. If the design of the routing system is not thought through, an attack on the integrity of the signal can happen. That can result in uncertainty in the measurements being made, and more importantly, put the integrity of the product about to be shipped in question (Figure 3).

Taking on this risk is not an attractive option. The goal of any system design becomes making the transmission path as transparent to the signal as possible without simply reverting to a manual setup. So, where do we start in an ATE signal routing design process to ensure that we have a reliable system in place—that is also repeatable, maintainable and provides the lowest cost of ownership over the life of the project? To begin, let's take a deeper dive into understanding how an interconnection system works against the systems engineer, and then what can be done to limit its impact on signal integrity. We will focus on path resistance, signal attenuation and insertion loss.

3.1. Path Resistance

This is the resistance that is added to a signal path due to cabling, connectors and switching. It is fundamental knowledge that a resistor in an electrical circuit provides several useful purposes, such as part of a filter network reducing noise interference or as an attenuator bringing high voltage signals into an acceptable range of a connected device. Resistance in an interconnect system, on the other hand, creates unwanted voltage drops, loss of transmitted signals and heat among a few side effects. Resistance in a signal routing system results in something less than what is expected at the signal's destination (Figure 4).

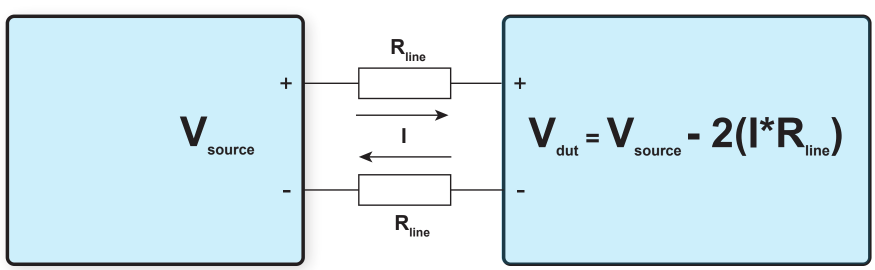


Figure 4 – Encountering loss due to resistance in the pa

As our previous example illustrates, it is quite easy to end up with tens of feet of wire in a signal path, and this presents issues for both DC and RF measurements. Since the diameter of a wire is directly proportional to path resistance, let's take a closer look at wire gauge and how it can alter test signals. Thicker, lower gauge wire obviously can carry more current than higher gauge wire. The increased diameter of copper in the conduit means that there is less resistance per foot of cable. Less path resistance means less power is dissipated, which also means less heat is generated. All of these are positive attributes for signal transmission. However, to facilitate smaller test system footprints on the production floor, high-density test instruments (particularly high channel count switch modules) and mass interconnects often use high-density connectors, which can only accommodate higher gauge wiring. Figure 5 quantifies the differences in path resistance between two common wire gauges used in ATE systems for carrying low level signals. Note that the specs are stated for a single conduit in free space. If the cables are bundled, the current carrying specs are significantly derated due to the heat that is generated. The higher gauge wire contributes 4x more resistance to the signal path.

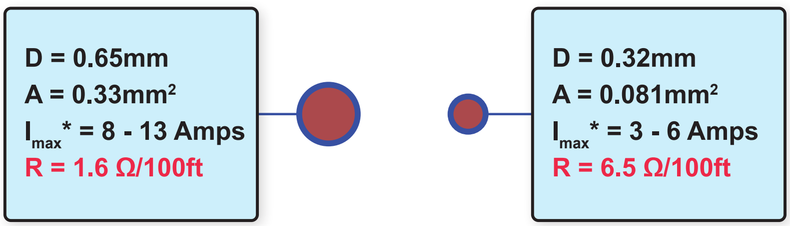


Figure 5. Quantifying lead resistance as a function of wire gauge

3.11. Example - set up

Let's get more specific using an application example in which hundreds of test points are to be multiplexed to a common input. In this application, the signals to be switched will not exceed 150 V or 1 Amp. Pickering manufactures high-density modular switching in the PXI format, including high-density multiplexer modules (Figure 6). Comparing the banner specs of each module, both meet the V/A requirement, however, one module offers a 25% increase in channel count. This is typically important in modular systems where slot space is a premium. The fewer slots a switching system occupies in a chassis, the more room there is for other instrumentation and future expansion. However, to achieve the higher channel density, a 200 pin connector is required, whereas the lower density module incorporates a 160 pin DIN connector in its design. The manufacturer of the 200 pin connector specifies that a minimum of 28 AWG wire be used in the mating contacts, whereas the 160 pin connector allows for a minimum of 20 AWG wire. But what does this mean to the system wiring and to what extent will it impact measurements through the switch?

PXI Chassis 		
Channels (2-wire)	99	79
Switched Volts	150V	300V
Switched Current	1 Amp	2 Amps
Ch Density	+25%	
Connector	200p LFH	160p DIN
Mating Contacts	36-28 AWG	28-20 AWG

Figure 6: Comparison of two high-density switch modules

3.12. Example - implications

To illustrate, let's say we are testing a product, and our test system is required to provide a 12 volt, 1 amp source, with a +/- 5% range of accuracy. We have built our system to route through multiple switches. As a result, there is 10 feet of cabling between the source and its destination point on the DUT, with the same length on the return path. (Figure 7). If our system is built using 28 gauge wire, the total path resistance is 1.3 ohms (disregarding any switch contact resistance). It is resulting in a drop of 1.3 volts—more than twice the allowable error. Using 22 gauge wire, the drop is reduced to 0.32 volts, which is within our error budget. Note that any switch and interface contacts in the path add to the total resistance, further contributing to the loss.

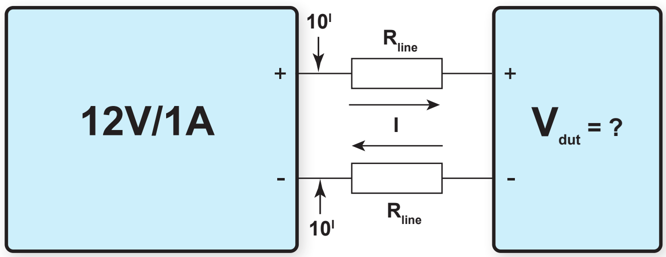


Figure 7 – Test system showing the cabling as resistance, with the voltage drop across the wire and the resultant voltage across the DUT.

	28 AWG	22 AWG
Wire Res.	6.5Ω/100'	1.6Ω/100'
Path Res.	1.3Ω	0.32Ω
V_{dut}	10.7 V	11.68 V
Error	10.8 %	2.7%

3.13. Example - solutions

The obvious conclusion is to keep wire lengths as short as possible to minimize lead resistance. When that is not possible, one common method for compensating for excess line resistance in a path is to use 4-wire source or measurement devices in which two high impedance sense lines run in parallel to the signal lines and make the appropriate adjustments to compensate for the loss regardless of cable length. Figure 8 shows a 4-wire measurement of a resistive-based sensor. If R_{DUT} is a 100Ω RTD, a 1 contribution of line resistance that would result in approximately 3.5°C error using a 2-wire setup, is nullified using a 4-wire measurement resulting in a very precise measurement. Any benefit comes with a cost, and the trade-off in this case is loss of system density since twice the number of switch channels will be needed to switch the additional sense lines. However, when absolute accuracy is required, implementing a 4-wire approach is generally the best option.

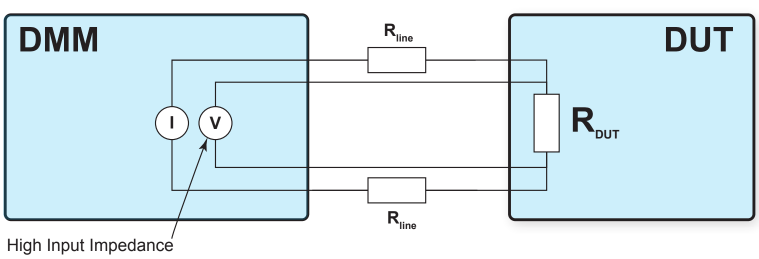


Figure 8 – 4-wire resistance measurements compensate for excess line resistance

3.2. Signal routing and AC measurements

ATE switching systems, particularly those that include RF measurements, are often architected with small building blocks. Examples include SPDT or SP4T relays that can be reconfigured using external wiring in test adapters to form several different topologies depending on the application requirement. This gives the systems architect a great deal of flexibility to fine-tune the switching network as needed. For example, a switching module with eight discrete SP4Ts can be repurposed with external coax wiring as a dual SP12T multiplexer to expand the I/O capacity of a 2-channel oscilloscope. For a different application, those SP4Ts can be rewired as a 4 x 4 matrix. The need for this flexibility is quite common in production environments where a high mix of products are tested on a common test platform. However, the flexibility does come with a hit in the performance that is associated with the additional coax cabling required to construct the larger switch networks. The selection of cable type can be of significance, depending on the application.

3.21. Example - set up

If we examine two commonly used coax cables in ATE systems, RG178 and RG316, many of the key specs are similar between the two as shown in the table.

Spec	RG178	RG316
Impedance	50	50
Gauge	30 AWG	30 AWG
t_{pd}	17.5 ns	17.5 ns
Capacitance	1.46 ns/ft	1.46 ns/ft
Attn. (@700 MHz)	0.37dB/ft	0.237 dB/ft
Attn. @12 ft	4.4 dB	2.8 dB

Table 1: Specification comparison of two types of 50 ohm coax wires

3.22. Example - implications

Both have identical propagation delays and capacitance per ft. Both are defined to operate in a 50 ohm environment; however, there is a noticeable difference in attenuation. If we consider a test setup in which there is 12' of coax cable between a source instrument that is sourcing a 140 MHz square wave to a device under test, the 5th order harmonic of that waveform is sitting at 700 MHz. The attenuation of that signal is a function of frequency, and there is about 1.6 dB of additional loss at that frequency using RG178. The loss will increase at the higher-order harmonics. If the cable length is increased, then the loss at 700 MHz will also increase. This can have a significant impact on dynamic measurements such as rise times and pulse widths as the higher-order harmonics contribute to the 'sharpness' associated with the edges of the waveform. Conversely, anything that can reduce the overall signal routing path will allow more of the harmonics to be resident in the signal, and the waveform shape will be less distorted.

3.23. Example - solutions

But what is the most efficient way of shortening signal path routes considering that longer cable lengths help maintainability of a test system by allowing for longer service loops? As usual, the discussion turns to acceptable trade-offs revolving around cost, system footprint, flexibility and performance.

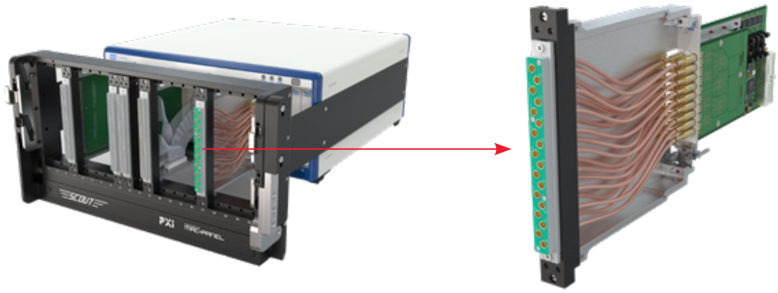


Figure 9 – PXI RF Switch module with integrated receiver connector (MAC Panel Scout system shown)

Since an ATE switching system is the hub of all instrumentation inputs and outputs, it is usually the device that occupies the most pins on the user interface. It is not unusual for a switching system to include thousands of contact points, which therefore accounts for the highest number of cables in the system. That means that reducing the distance between the user termination (or test system receiver) and the system switch will have the most impact on reducing overall system cable length.

If the switch is in a PXI chassis with other instruments, one option to be consider it to place the chassis directly behind the connection panel to shorten the distance. If you are using a Virginia Panel or MAC Panel mass interconnect receiver assembly, significant cable reduction can then also be achieved by integrating the switch with a receiver module through the use of a funnel assembly. Wiring from the switch module is contained in very short runs inside the funnel. While the up-front costs for mass interconnects with funnel assemblies are higher when compared to discrete cables, the return can be made up through improved serviceability and performance (Figure 9).

Figure 10 – Pickering Dual SP16T (L), and Octal SP4T (R)

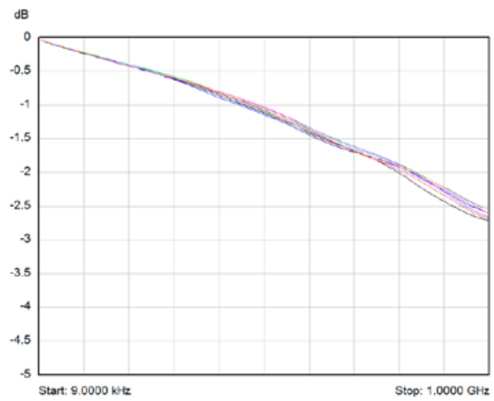
Finally, it is wise to also consider the topology of the switching modules used to construct the switching system as a potential avenue to shorten cable lengths. Modules with multiple SP4T switches, such as Pickering's 40-749-511 RF multiplexer card, provide excellent design flexibility. However, when a large multiplexer is needed, such as in extending a scope channel to 16 test points, cabling to and from the interconnect panel is required to connect these blocks, and the path length and capacitance quickly increases. Switch modules internally configured as larger multiplexers, such as Pickering's 1 x 16 40-875-001, limit the flexibility; however, they facilitate a significant reduction in cabling. (Figure 10).

3.3. Insertion loss and impedance mismatch

The issues we have discussed so far describe the impact system wiring has on the overall integrity of a transmission path. When transmitting signals that have higher frequency components, a key specification of interest is bandwidth. Bandwidth ultimately defines the highest frequency signal that can be passed through a transmission line. In an ATE system, bandwidth is governed in part by the insertion loss at the various connection points in the signal path. Switch contact points and interconnects provide ample opportunity for impedance mismatches that reduce system bandwidth.

40-760, SP4T*

Insertion Loss



40-762, SP16T*

Insertion Loss

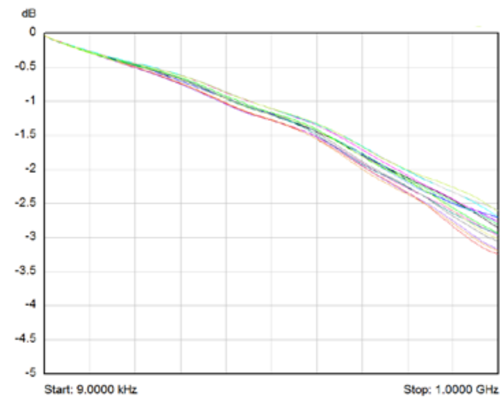


Figure 11 – Insertion loss as a function of relays connected in series

Contacts and switches are typically specified for insertion loss at a frequency at which the power received through the switch is half of that generated by the source, which occurs at the -3dB point. If you consider that multiple relays can end up in a signal path, the cumulative effect of insertion loss can be significant, even at lower frequency signals. Figure 11 shows insertion loss plots for two Pickering switch modules, one is comprised of individual SP4T multiplexers, the other includes internal wiring connecting SP4T relays in series to form SP16T multiplexers. Insertion loss is cumulative, and the SP16T module's effective bandwidth at the -3dB point is reduced accordingly.

Non-sinusoidal waveforms are comprised of multiple harmonics. Even a 140 MHz square wave will be impacted by a switching system that has an overall bandwidth of 500 MHz since the higher-order harmonics that contribute to the sharpness of the edges will be dampened, impacting the fidelity of the square wave as discussed in the previous section.

Therefore, it's important to ensure that the switching components selected, and the signal path routing system, provide enough headroom to satisfy the test requirements with which you are presented. But also consider that the system you are designing today may be required for other needs later on.

3.4. High Voltage

Cable capacitance is often attributed to signal integrity issues in RF systems, though line capacitance is largely distributed across the path. Capacitance can wreak havoc in DC systems as well, where high voltage signals are being switched through a multiplexer to a measurement device. Take, for example, the instance of a multiplexer relay being closed to make the connection between a measurement device and a 400 V source, followed by a measurement of a low voltage signal. The capacitance in the line charges to the signal level, but in this case, that level is at a high common mode.

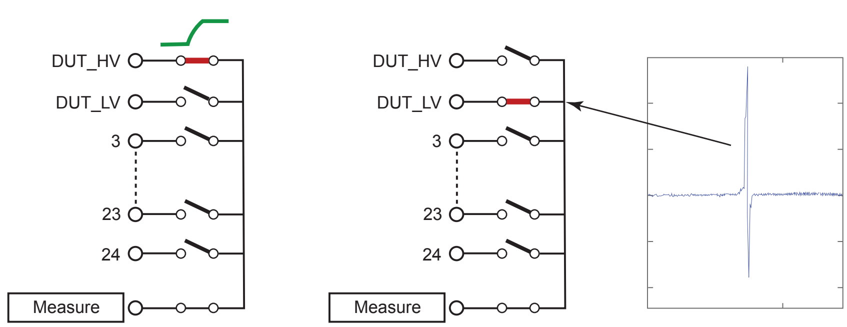


Figure 12– High voltage spikes can weld a relay shut

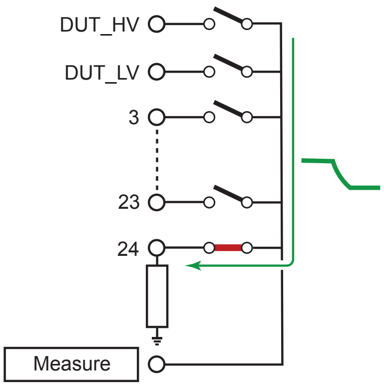


Figure 13 – Using a discharge path to dissipate stored energy

The measurement is completed, and the switch is opened. However, there is no path through which the cable can discharge the stored energy. When the next relay is closed to connect to the low voltage circuit on the DUT, the cable rapidly discharges its energy resulting in a very high voltage spike. These spikes (Figure 12), while short in duration, can be multiple kilowatts—enough to weld a relay shut and in the worst case, damage the product being tested or the instrument making the measurement.

How can this be avoided? One common method is to dedicate a switched channel as a discharge resistor (Figure 13). After every high voltage measurement, the multiplexer can be switched to this dedicated channel to bleed off any stray charge before moving onto the next measurement. It's an extra step for each measurement, but the prevention of unwanted voltage surges is well worth the trade-off.

4. Gigabit Ethernet and other high-speed interfaces

Gigabit Ethernet, USB and other high-speed serial communications interfaces have become prevalent in products in the automotive, semiconductor, defense and aerospace industries. It can be challenging to preserve these signals since they can be low power and ever-higher frequencies. The original USB specification was limited to 12 Mbit/s, while the latest proposal for USB 4 is planning for speeds more than 3,000 times faster: up to 40 Gbit/s. (Figure 14) Ethernet likewise has evolved to operate at higher speeds and with fewer data-carrying lines. Single-pair Ethernet is an emerging technology targeted toward automotive applications that aim to bring the same high-speed data as CAN or other standards with fewer connections and simpler cabling.

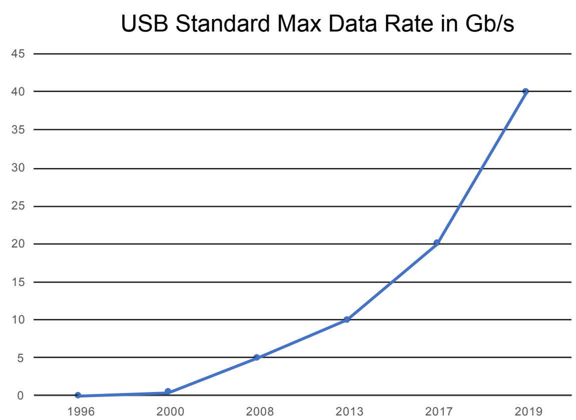


Figure 14 – USB 4 is 3000x faster than the original specification

These signals can be particularly challenging due to their low power and higher frequencies requiring appropriate cabling to preserve the signal. Their connections also require matching the impedance, performance, and other specifications defined by each technology's standards organization. USB and Ethernet both use twisted-pair cabling to reduce crosstalk and interference from other signals. Some versions of these standards also require shielding in the cable for the same reason. Adding these features can increase the complexity, size and cost of the cable. As always, these trade-offs must be considered in the context of the larger test application.

5. Designing custom cables

Once the design goals are understood and acceptable trade-offs determined, the task of designing the cables for manufacturing is typically difficult. Many organizations do not have a dedicated software tool for defining cables, connectors, or their pinouts. This can result in confusion or missing detail in the design, as well as a lack of documentation, which can make it difficult to reproduce or standardize any cables used.

Therefore, especially in the case where there is no dedicated in-house resource available, test teams will work with custom cable manufacturers who can help with the selection of components and by providing documentation on a finished design.

5.1. Pickering Interfaces' Cable Design Tool

Another option is to use a design tool like the one offered by Pickering. The Cable Design Tool allows users to define all aspects of a cable, including connectors, wiring and pinouts. The tool also generates documentation, including a bill of materials and a graphical representation of the final cable. This document facilitates the manufacture of standard cables, and it can be included in the definition of a test platform. (Figure 15).

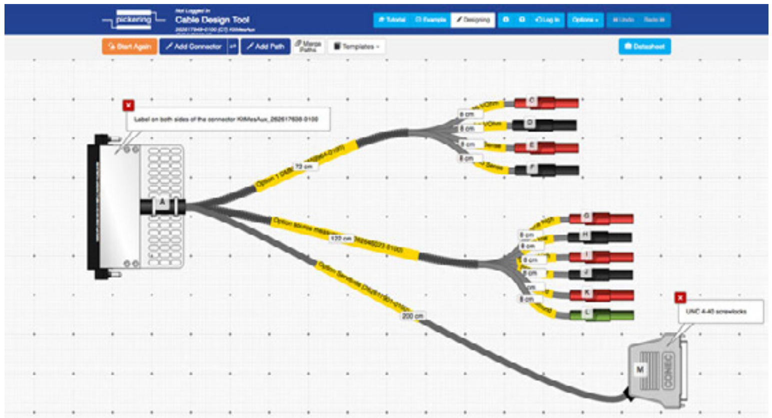


Figure 15 – Pickering's free Cable Design Tool

Summary

Signal routing for test would be considered to be perfect if the path between the test instrument and the device under test was electrically 'invisible'. Of course, this is asking the impossible. The serious point here is that test engineers need to take care of the whole measurement channel by considering everything between the instrument and the DUT, including cables, switching subsystems, connectors and mass interconnect products.

The best switch module is rendered virtually useless unless the cabling and the connector types are appropriate for the application. Too small a wire gauge results in increased lead resistance, causing serious voltage drops that impact test results. A long cable may have too much capacitance and signal attenuation. The result can be damage to your switches and even the DUT when discharging the energy in the cable, and it can turn a fast-rising signal into a slow, rolling waveform. Poor connectors may wear out too soon, creating intermittent problems; EMI may be an issue, and there are many other factors to consider.

Figure 16 – Pickering's modular switching portfolio

Selecting a flexible switching platform that can cover a range of application requirements and provide for future expansion provides a solid foundation for a test system design. Pickering's modular switching portfolio provides maximum flexibility for system designs offering the widest range of products covering DC to light. (Figure 16).

Finally, in some cases, cables are supplied with switch modules, so they will have been designed to work with that module. If not, adhering to the specifications of the switch module is best practice. Pickering Interfaces has a dedicated facility that produces cables and accessories to ensure that the performance of the switching module is not compromised by poor interconnections.

About Pickering Interfaces

Pickering Interfaces designs and manufactures modular signal switching and simulation for use in electronic test and verification. We offer the largest range of switching and simulation products in the industry for PXI, LXI, and PCI applications. To support these products, we also provide cable and connector solutions, diagnostic test tools, along with our application software and software drivers created by our in-house software team.

Pickering's products are specified in test systems installed throughout the world and have a reputation for providing excellent reliability and value. Pickering Interfaces operates globally with direct operations in the US, UK, Germany, Sweden, France, Czech Republic and China, together with additional representation in countries throughout the Americas, Europe and Asia. We currently serve all electronics industries including, automotive, aerospace & defense, energy, industrial, communications, medical and semiconductor. For more information on signal switching and simulation products or sales contacts please visit: pickeringtest.com

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