Finding the problem in a complex interconnect layout can be difficult and time consuming. Using state-of-the-art Vector Network Analyzers (VNAs) and new software packages offers breakthrough solutions for the digital designer.

There is a great upside to bleeding-edge technology. That upside is the ability to do more, with less, faster and with less power. That upside, however, has baggage - complexity. High-speed digital designs are bumping up against RF fields, creating a new set of design issues. Tighter integration, three-dimensional devices and circuits, and multi-layer back planes, all packed denser than ever on physical real estate, have created a real challenge for digital design engineers. That translates into increasing difficulty for the designer to take direct measurements in today's complex structures. Therefore the best solution is to characterize the device, in either the time or frequency domain (depending upon circumstances), with S-parameter measurements.

The first paper in this series was the introduction into working with and transforming general oscilloscope acquisitions. This is the second paper in this series and will discuss interconnect testing and present solutions based on the latest generation of test software (PLTS 2012) for Keysight Technology, Inc.:s line of performance network analyzers (PNAs). Specifically, it will address the new capabilities in the software.

The hardware platform is the performance network analyzer (PNA). The software platform is the physical layer test system (PLTS) software — a powerful signal integrity tool for today's high-speed digital designers. The latest release of PLTS version 2012 software incorporates industry-first capabilities including: MATLAB compatibility enabling powerful built-in features as well as the ability to run user specific MATLAB script, data integrity check and enforcement for simulation engine compatibility, multiple channel eye diagram analysis featuring multiple aggressor crosstalk, and advanced automatic fixture removal for non-symmetric fixtures. This document will discuss these features and the procedures involved. However, before we proceed with the analysis, it would be prudent to define what is meant by interconnects. For this discussion, interconnects are characterized by two features - linearity and passivity. Such devices include PC boards, backplanes, cables, connectors and IC packages – anything that isn’t powered.

All linear and passive devices that transmit gigabit data require physical layer testing. Fast gigabit data can’t propagate through copper traces that aren’t designed for high speed. The concept of optimizing copper interconnects is required to realize high speed digital systems. This is what PLTS can offer engineers who are pushing the state-of-the-art. The rest of this document will detail the new capabilities of the PLTS.

To test interconnects, a signal is sent into the device under test (DUT). A time domain reflectometer (TDR) sends a step, a vector network analyzer (VNA) sends a sine wave. Both instruments then measure the response. This is called stimulus/response testing and is what Keysight’s Physical Layer Test System is designed specifically to measure.
The Perspective

In today’s high-speed circuits, data rates are clocking so fast that interconnect devices are acting like transmission lines. Normal design rules no longer accurately define interconnects. Fast clock and rise times of these high-speed circuits create problematic electromagnetic interference/electromagnetic compatibility (EMI/EMC) issues. Interconnect, depending upon type (cable trace, connector, etc.), can assume a number of electronic conditions. For example, inductors can become predominantly capacitive at high frequencies due to the parasitic coupling between windings. As well, a capacitor can develop parasitic series inductance due to its internal inductance and external lead inductance at these super-clocked frequencies.

A via, for example, acts as a small capacitor coupling to the plane and lowering the impedance. Conversely, a small jumper wire can act inductively because it rises off the board and away from the ground plane. Another example is that the faster the data clocks, the more pronounced skin effect becomes on circuit traces. Interconnect designs are now multi-directional and multi-planar. Crosstalk is critical now, affecting signal integrity like never before.

Modern fast rise times of tens of picoseconds create high overshoot and pulse settling creates new noise issues. Put all of this together and it becomes difficult to physically measure interconnect in today’s gigabit-speed circuits. Therefore, device characterization becomes the only way the engineer can determine the actual performance.

The Initial Approach

Engineers have found themselves in a place where they are tasked with trying to measure a behavioral model of a specific structure in a sea of interconnects. Perhaps it is the via, trace, connector, cable, or even the interface. The engineer needs to utilize de-embedding techniques quickly, efficiently and accurately.

Simply stated, a test fixture needs to be designed and its characteristics determined. Then, the DUT can be analyzed with the fixture and the known variables eliminated so that the device characteristics are known. While simple in theory, accurately designing a fixture, embedding, measuring and de-embedding requires a methodology that is more complicated than it appears.
Using traditional hardware and software, once the fixture has been identified and modeled, the initial approach was to assume that the modeled and physical fixtures were identical and symmetrical in both return and insertion loss. However, modeled structures generally assume ideal parameters and peripheral effects such as return and insertion losses vary the actual device performance. The Keysight PLTS has a non-symmetrical option, which allows the AFR (Automatic Fixture Removal) function to consider non-symmetrical devices, assuming only equal insertion loss and electrical delay.

Traditionally, to utilize an S-parameter as a device model in a simulation environment, there are three conditions that need to be validated; passivity, reciprocity, and causality. The applicable formulas to determine these conditions are:

**Passivity**
The passive condition is all Eigen values of S matrix have magnitude ≤ 1. For N Port DUT, |Snm| ≤ 1; n, m = 1, 2, 3 ... N

**Reciprocity**
The Reciprocal condition for passive N port DUT is:
Snm = Smn; n! = m; n, m = 1, 2... N.

**Causality**
The spectrum causality condition is given by Kramers-Kronig relations that state that the real and imaginary parts of a causal response are related by the following Hilbert transforms:

\[ u(\omega) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{v(\omega')}{\omega - \omega'} d\omega' \]
\[ v(\omega) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{u(\omega')}{\omega - \omega'} d\omega' \]

were \( u \) and \( v \) are real and imaginary parts of the spectrum respectively. \( P \) is the Cauchy principal value. Note: For a passive component, due to measurement noise or numeric error, the measured S-parameters may be slightly non-passive at certain frequencies. The causality violation of the impulse response, namely non-zero response at negative time, is due to the spectrum truncation in the S-parameter measurement.

With the new hardware and software, data is simply entered into the graphical user interface (GUI) of the PLTS. PLTS checks and/or enforces the passivity, reciprocity, and causality of the S-parameters. It leverages the patent of “Optimization of spectrum extrapolation for causal impulse response calculation using Hilbert transform” from the Keysight Advanced Design System (ADS) for passivity and causality enforcement.
The Setup

Keysight’s PLTS has integrated a host of new features and offers a test suite series wizard to assist the engineer in setting up the process. The remainder of this app note walks the engineer through the process of analyzing the high-speed networks using the latest features in Keysight’s PLTS software, and working with the S-parameter that will be developed by the process. For this discussion, a multi-channel eye diagram concept will be used.

One advantage of the advanced PLTS system is that it can inject a number of transmitter imperfections into the DUT. These include adding various types of jitter, including random (RJ), periodic (PJ) and inter-symbol interference (ISI). It has the ability to add source noise by specifying the signal-to-noise (SNR) per symbol or (EsNodB). It can add source equalization and crosstalk from sources on other ports as well.

To begin the setup, open the tools menu, using (GUI), and select “multi-channel eye diagram” (see Figure 2). This GUI uses the standard “Windows” interface so common terms such as click, drag, select, edit, etc. will be used. It is assumed the reader is familiar with the Windows interface.

First, drag the transmit (Tx), receive (Rx) and crosstalk (Xtalk) components to the blank slots to set up the channel configuration. The channel configuration is dependent on the DUT configuration so select (by clicking) the components to edit the settings of Tx, Rx and Xtalks. If further refinements are desired, the user can bring up the advanced eye diagram screens to tweak the settings (see Figure 3). Once the desired setting are confirmed, (see Figure 4), click the “Draw Eye” button. The software calls Matlab runtime dlls for the simulation and draws the eye diagram results in PLTS.
In the event that the fixtures do not have the same electrical length, there is the option to add a second Thru using automatic fixture removal. The first Thru is the cascaded combination of the left fixture and its mirror image, the second Thru is the cascaded combination of the right fixture and its mirror image. With the two Thrus, the left and right fixtures can be characterized separately and de-embedded from the composite DUT measurement (see Figure 5).

There are a number of other options and features in PLTS 2012. A more detailed description of these is available at www.keysight.com/find/plts
Collaboration with MATLAB

Once the data has been acquired and logged, it can be inserted into Mathworks' MATLAB for collaboration with Keysight's PLTS. This is the unique function of the Keysight platform, which allows easy data interchange between time and frequency domains.

The first step is to select the tools menu from the home page of the GUI. Select math then collaborate with MATLAB (see Figure 6). Then browse for a MATLAB file for the specific transfer function desired (a). Next, map the MATLAB function argument with the PLTS data (b). Third, select a result (c). Finally, name (d) and save (e).

Figure 6. Initiating the MATLAB function.
Once the equation has been derived, it can be displayed in a number of different ways, from the “apply equations dialog” box on the display (see Figure 7). The process is simply to select the equation content (1), pin or unpin from the bottom pane (2.1), and click the apply button (3.1). The equation is sent to the viewing device. Equations can be saved in both PLTS and MATLAB formats.
The Eye Analysis

Once the data has been accumulated, it can be related to the actual eye diagram as displayed on the oscilloscope (see Figure 8). The selected measurement result can be chosen from the display box and shown as a resultant time domain graphic on the screen. Other desired parameters can be read from the eye diagram as well (amplitude, width, rise/fall times, etc.).

![Eye amplitude](image)

![Eye width](image)

![Fall time](image)

Figure 8. Eye diagrams and related parameters.

Once the reader is familiar with the measurements, there are any number of analyses that can be obtained. It is possible to use PLTS to view the transfer functions in either time or frequency domain. The results in Figure 8 are in the time domain.

Conclusion

This discussion has revolved around using Keysight’s PLTS to assess the performance of high speed digital interconnect and analyzing the results. The versatility of the PLTS platform offers the engineer the ability to fully and thoroughly analyze interconnect by measuring a wide variety of parameters. This can be done by direct interconnect or indirect by way of fixtures. The data collected is inputted by way of PLTS, Windows standard GUI. As well PLTS can collaborate with MATLAB to optimize the data and present results for any number of time or frequency.

This paper has discussed obtaining data in the frequency domain. The next paper will discuss collecting data in the time domain.
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