A NOVEL LOW COST APPROACH TO 4 PORT NETWORK ANALYSIS UP TO 40 GHZ FOR SIGNAL INTEGRITY MEASUREMENTS ON GIGABIT BACKPLANES

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Introduction

In the world of high-speed digital design, clock rates are increasing at a dramatic pace. Gigabit per second data rates are creating signal integrity problems for printed circuit board structures such as backplanes, micro-strip traces and interconnects. Data rates have dramatically increased from the Megabits to Gigabits per second range, all enhanced by switching from parallel to serial data transmission. Typically such standards are: 8 Gbit/s PCIexpress Gen 3, 6 Gbit/s Serial Attached SCSI (SAS) Gen 2/Serial Advanced Technology Attachment (SATA) Gen 3 and 10 Gbit/s Gigabit Ethernet. All serial transmission is no longer carried through mere copper traces, but actually impedance controlled transmission lines.

This significant change in data rates has added new constraints to the design of the lines carrying these signals. Factors that were normally ignored at lower data rates are now part of specifications at higher rates, such as crosstalk between lines, dielectric effects, Inter-symbol Interference (ISI). The below figure 1, depicts the voltage and timing factors that affect data transmission, as rates increase from the Mega bit/second to the Giga bit/second range.

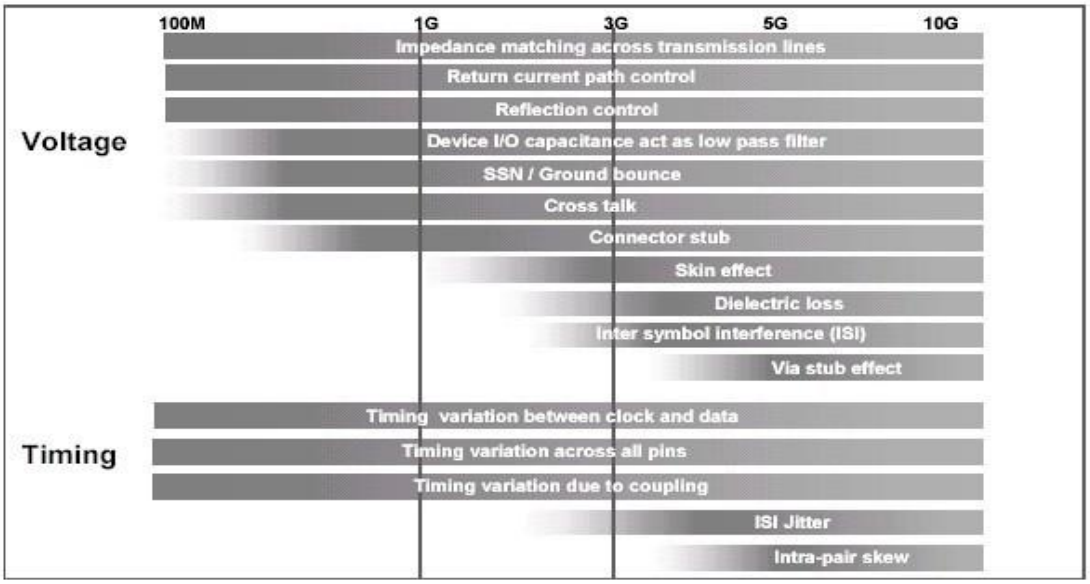


Figure 1: Voltage & Timing effects on Serial data signal streams within a printed circuit board link.

One of the critical parameters is the quality of the transmission lines, characterized by a technique called Time Domain Reflectometry or TDR. TDR is as much a part of serial data analysis as is Jitter and is often performed in conjunction with it, although typically with different equipment[1].

The General Signal Integrity Problem

Consider a simple serial data link with differential lines using NRZ (non-return to zero) coding on a simple backplane, as shown in figure 2 below.

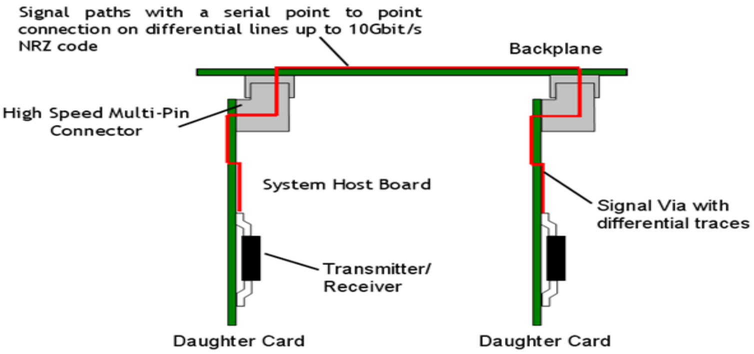


Figure 2: High speed passive server backplane with transceiver cards.

Signal integrity directly affects the performance of the transmission link. The main causes of poor signal integrity include reflections, frequency response and crosstalk. As can be seen in the figure 3 below, e.g. reflections can cause the eye diagram, to 'pinch' inwards reducing the voltage margin.

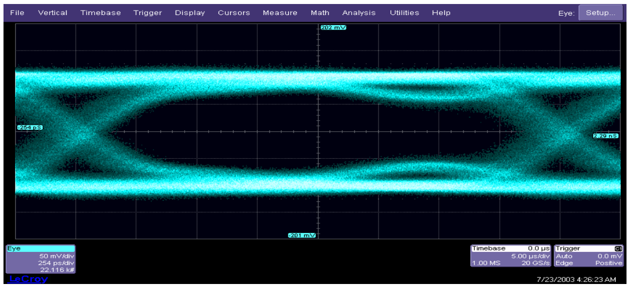


Figure 3: Serial data Transmitter Eye diagram (NRZ) typical of Gigabit/second data rate showing reflection distortion on both top & bottom of the eye to the right of centre, impinging on the central region.

The transmission lines and components which transmit and receive the data are bandwidth limited. This will cause rising and falling edges to be non-ideal. The first bit after a transition may not reach proper amplitude until after a significant period of time. For this reason, some systems use "pre-emphasis" which drives the leading edges harder at the output of the transmitter and in addition, equalization is usually applied at the receiver[2]. Typically without correction the edge timings are displaced in the 'eye' diagram, rather than showing a clean crossing point at a 50% threshold, as can be seen in figure 4 below.

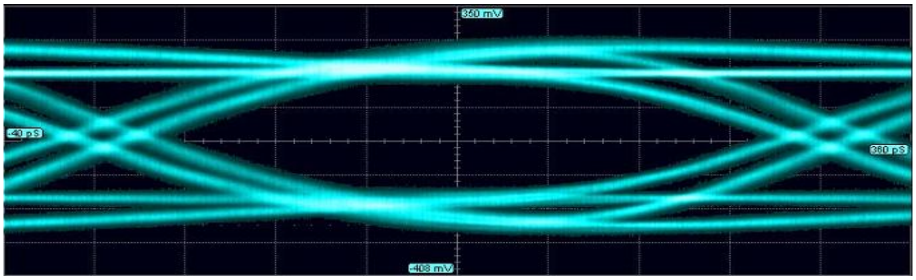


Figure 4: Eye diagram showing insufficient bandwidth due to channel limitation, causing ISI distortion, evident as multiple crossing points on the Eye.

Basics of TDR/TDT

Figure 5 shows a simple block diagram for a typical TDR measurement. The time domain reflectometer (TDR) employs a step generator and an oscilloscope in a system which might be described as "closed-loop radar." In operation, a voltage step is propagated down the coax cable to the device under test (DUT). As an impedance discontinuity is encountered in the DUT, some of the energy is reflected. Both the incident and reflected voltage waves are monitored on the oscilloscope at a particular point on the line.

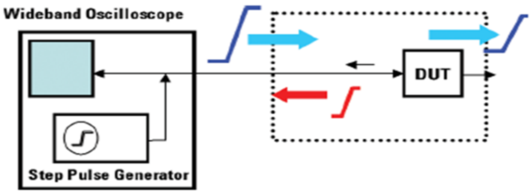


Figure 5: Simplified TDR system with wide bandwidth sampling (or real-time) scope typically 20 GHZ or higher

A step generator is required to generate the input pulse to the DUT. The resulting voltage reflections, including the incident voltage step, are sampled by the TDR module and measured by the scope. An insight into the shape of the resulting reflected voltages yields more information on the discontinuity, including its location within the device.

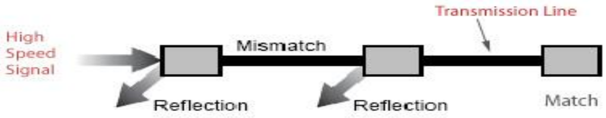


Figure 6: Reflections from impedance mismatches caused by connectors, via's (Vertical Interconnect Access) etc.

The signal measured by the scope is the composite voltage signal of the incident, as well as the measured reflection from the device, as outlined in figure 6 above. There are two main factors that affect quality of signals transmitted through a media. 1) Impedance match of the traces, which is characterized by a TDR measurement, and 2) Loss through the transmission media, which is measured via TDT or Time Domain Transmission. Contrary to TDR that measures the reflections from a device, TDT measures the effect on a step pulse transmitted through a device, in terms of rise time, loss etc. A TDT measurement, converted to frequency domain using FFT, is called the Insertion loss over frequency of a DUT, also known as the Transmission S-parameter. In short, Time Domain Transmission (TDT) measurements are used to determine the effect a network has on the transmission of a pulse signal travelling through it. For a TDT measurement, a step generator is used or TDR module and in addition, another module to measure the transmitted signal. This extra module over the TDR case, could be another TDR or sampling module, that covers the same or higher frequency, shown below figure 7.

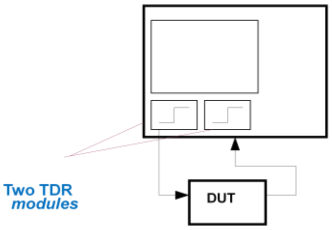


Figure 7: TDT block diagram, showing that a separate transmit & receiver sampler module are required over the TDR case

Returning to the TDR case where we have a matched condition (50 Ohms) with no reflections, after the initial step, the line is flat on the sampling scope, as can be seen below, figure 8.

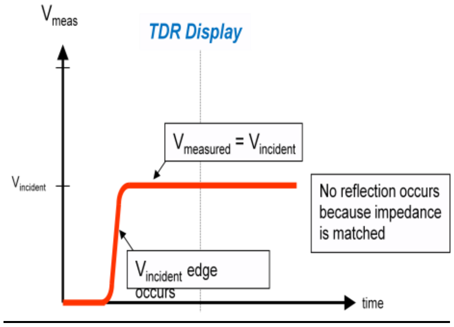


Figure 8: TDR response with a 50 Ohm single ended or 100 Ohm differential match

If a real transmission line is ‘interrogated’ via cable or TDR probe, we do not see a perfect match, but perturbations caused by capacitive or inductive coupling. Inductance in this case tends to leads to a rise in the reflected voltage, appearing as it were as an instantaneous open circuit, returning more power than the matched condition. However, the opposite is the case for a capacitive load, where this appears for an instant as a voltage short, but again reflects back energy to the source this time with inverted polarity, see figure 9.

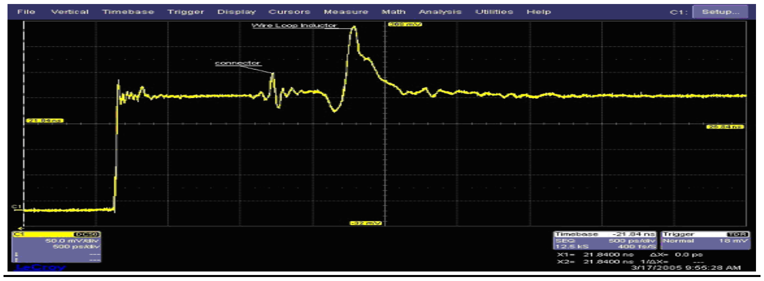


Figure 9: TDR trace from a 5 cm long transmission line on a 20 GHz sampling scope, showing connector discontinuity and wire loop inductance (large positive spike) and some parasitic capacitance on both, evident as negative going peaks.

S-Parameter Measurement Methodology

The SPARQ Signal Integrity Network Analyzers uses TDR/TDT to characterize a network’s electrical behavior and outputs this data, as either single ended or mixed mode S-parameter measurements. The process to measure S-parameters includes 3 phases: 1) OSLT (open, short, load, through) calibration, 2) DUT (device under test) measurement, and 3) S-parameter calculation, including de-embedding. When using “E” model SPARQs, all phases are done automatically, with a single button press, and without any user intervention whatsoever. This is accomplished by routing signals through the SPARQ’s internal switch matrix assembly. The key to the measurement process is the SPARQ’s acquisition system. The SPARQ acquires waveforms from the TDR and TDT sampler modules using LeCroy’s Coherent Interleaved Timebase (CIS), which generates a sampling strobe that is designed to slip over the entire waveform, coherently sampling at an effective rate of 204.8 GS/s. A 14-bit ADC routes sample data to an FPGA that reconstructs the waveforms and performs fast averaging. The amount of averaging is user-selectable via the “Accuracy” selection of the users interface, with nominal values of 250, 2500 or 25000. By increasing the number of averages, users increase the dynamic range of the S-parameter measurement. The SPARQ “hardware averages” 250 waveforms at a time in approximately 1 second, and transfers the average of the 250 waveforms to a PC running the SPARQ application software[3].

Automatic OSLT Calibration

The “E” model SPARQs, including the 2,4,8 & 12 port models, utilize an internal OSLT calibration kit that is permanently attached to the SPARQ’s switch matrix assembly. During an automatic calibration, the TDR pulse is routed via the switch matrix to the open, short, and load standards, and then via a calibrated “thru” to a second sampler. At each of these steps, TDR pulses are issued and TDR waveforms are acquired. When attached to the “Thru”, TDT waveforms are acquired as well. Prior to measuring the calibration standards, a baseline measurement is performed. The baseline trace is subtracted from all traces to assist in eliminating deterministic error, left hand most image, figure 10.

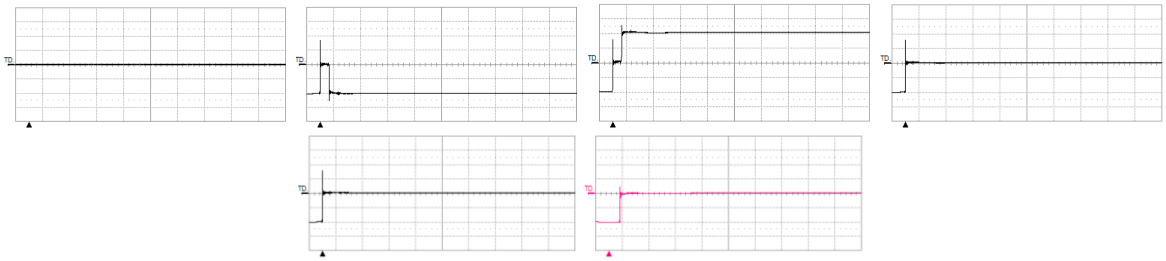


Figure 10: Calibration phase above, includes baseline correction followed by short, open, load and thru standards. When using an “E” model SPARQ, this phase proceeds automatically by routing the TDR and TDT pulsers to an internally connected calibration kit.

During the measurement phase, a sequence of steps is executed in which the samplers that acquire TDR and TDT waveforms are connected to pairs of DUT ports. All combinations of port-pairs are included in the sequence, such that all DUT ports are characterized using both TDR and TDT with every other port. Unused ports in each step of the sequence are routed to 50 ohm terminations, this process being no different than when a VNA is used. TDR pulses are issued at a rate of either 1 or 5 MHz, depending on the selection for DUT Length mode and TDR and TDT waveforms are acquired, figure 11.

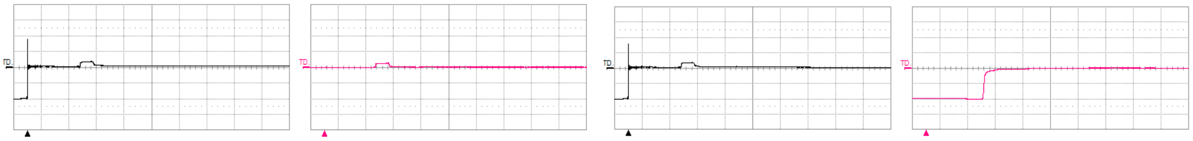


Figure 11: Example TDR (black) and TDT (red) acquisitions. The left image shows waveforms acquired when connecting TDR to port 1 and TDT to port 2. Here, the TDT waveform is showing crosstalk between ports 1 and 2, which are not directly connected. In the right image, TDT is connected to port 3, and shows the edge coming through the DUT.

The S-parameter calculation phase takes place in the user’s PC. Each averaged TDR and TDT waveform acquired in the measurement phase is processed as follows, figure 12:

1. The waveforms are input to a wavelet de-noising algorithm that further eliminates remaining uncorrelated noise.
2. The “de-noised” waveforms are split to separate out incident and non-incident (i.e. reflected and/or transmitted) components.
3. The separated waveforms are differentiated to obtain impulse response waveforms.
4. The separated impulse response waveforms are transformed to the frequency domain via a Chirp Z-transform. The user’s selections for End Frequency and Number of points are used to establish the frequency span and resolution.
5. “Raw” S-parameters are obtained by taking appropriate ratios of the waveforms input to this step. For example, the ratio of the frequency-domain waveforms that were transformed from the reflected and incident impulse responses from port one, is the raw S11 S-parameter.
6. S-parameters referenced to the front-panel ports are calculated from the raw S-parameters via an algorithm that takes as input, the error terms determined from the calibration phase and the S-

parameters of all paths through the switch matrix. (S-parameters of the switch matrix are measured at the factory, and are stored on the SPARQ's SD memory card.)

7. S-parameters of the DUT alone are calculated via an algorithm that de-embeds attached cables, adapters and fixtures. The de-embedding is done by using the S-parameters of these components, which are input to the SPARQ application. (The S-parameters of the cables are measured at the factory, and are stored on the SPARQs SD memory card.) When selecting to enforce reciprocity, the solution set is constrained such that Sij = Sji
8. When passivity enforcement is selected, the SPARQ returns an S-parameter matrix that meets the condition ||S||2 <= 1. ||S||2 also called the 2-norm, is the largest singular value of the matrix S. If the S-parameter matrix is found to not meet this condition, then it is perturbed by a minimum possible amount by a matrix A such that ||S-A||2 <=1. (S-A) is the S-parameter matrix meeting passivity.
9. When causality is enforced via the user interface, the following analysis is performed:
    A. The impulse response for each S-parameter is computed by taking the inverse FFT.
    B. When the maximum causality length is selected as = 0, the 2nd half of each impulse response waveform data is set to 0. When the maximum causality length is greater than 0, sample points at times greater than the selected causality length are set to 0, with the requirement that the 2nd half of the impulse response waveform will always be set to 0.
    C. The resulting impulse response waveforms are transformed back to the frequency domain via a Chirp Z-transform, yielding S-parameters that meet the desired causality condition.

At the end of the calculation phase, S-parameters are displayed. Users can choose to display S-parameter magnitude or phase, as well as mixed-mode or single-ended S-parameters. Time-domain views including step response, impulse response, rho and Z can be displayed. These are calculated by performing an inverse FFT on the measured S-parameters to obtain the impulse response, and then by convolving with an impulse. The impulse's integral is a raised-cosine step function with a user-selectable risetime.

Wavelet De-noising

Denoising algorithms have the effect of removing broadband noise from the acquisition primarily through means of detecting where uncorrelated noise is present in the signal in time. A conservative method considers the fact that the primary noise reduction occurs where there are no reflections. In other words, if we look at a denoised waveform, the primary effect is to remove the noise in the locations in the waveform devoid of reflections. The effect on the noise is to retain only the portion of the waveform that contains reflections and it is assumed that the noise remains in these portions. By using Wavelet denoising to remove noise this improves dynamic range by nominally 10 dB, figure 13. It is beyond the scope of this paper to go into depth on this subject, but further information can be found in reference[4].

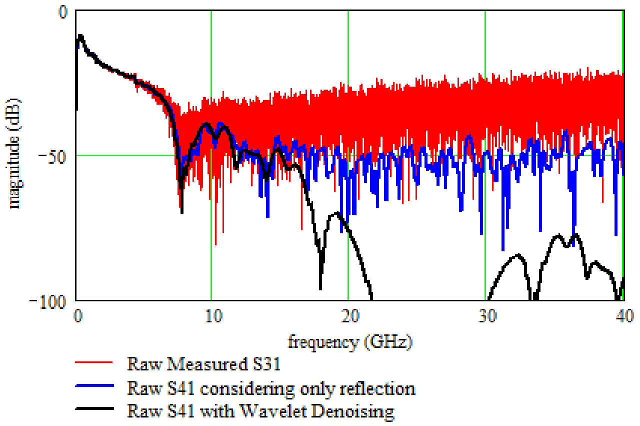


Figure 13: Frequency Content of Denoised Crosstalk Measurement

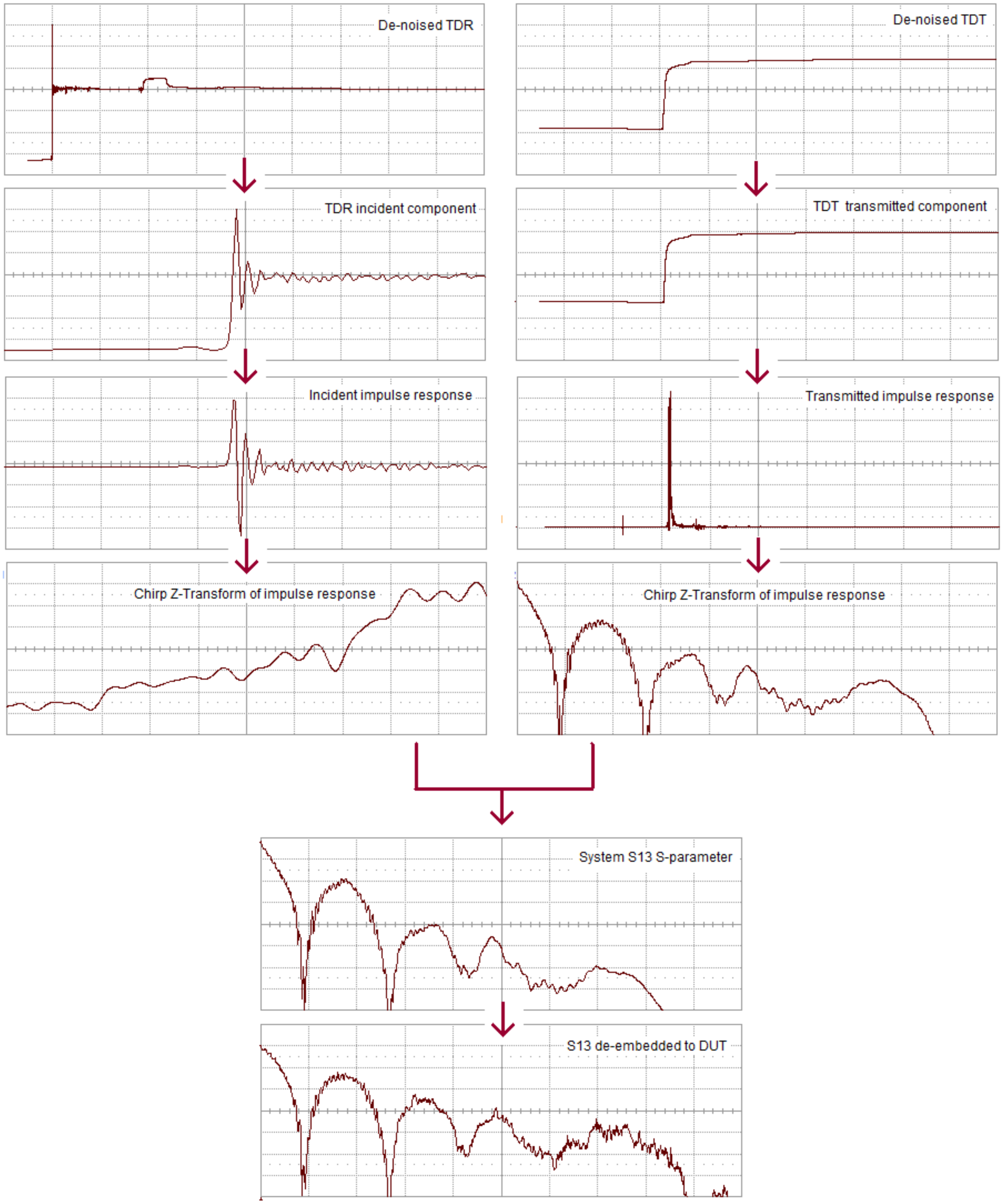


Figure 12: Example illustration of the calculation of the S13 parameter for a DUT where port 1 feeds through to port 3.

SPARQ Architecture

The TDR/TDT based acquisition system in the Sparq uses a 6 ps TDR risetime yielding giving a 40 GHz system bandwidth. The LeCroy CIS timebase acquires 250 waveforms/sec through a 40 GHz switches & routes signals to the internal calibration standards kit and to pairs of ports, as required see figure 14. The measurement reference plane of the instrument is at the Sparq ports on the front of the casing, but calibrated cables are also supplied with 2 port S-parameter touchstone files, to allow de-embedding up to the end of these cables. A typical technique for TDR based analysers is to use ‘gating’ to remove parts of the TDR trace in the time domain to subtract unwanted components such as; test fixtures, connector & cables not part of the actual DUT. By using de-embedding, external parts of the system connecting to a DUT can be removed from the S-parameter data, as we do internally for our own switch matrix assembly, as shown in figure 15. By including the S-parameter data of all attached parts connecting to the DUT the de-embedding algorithm returns only the S-parameter data of the DUT.

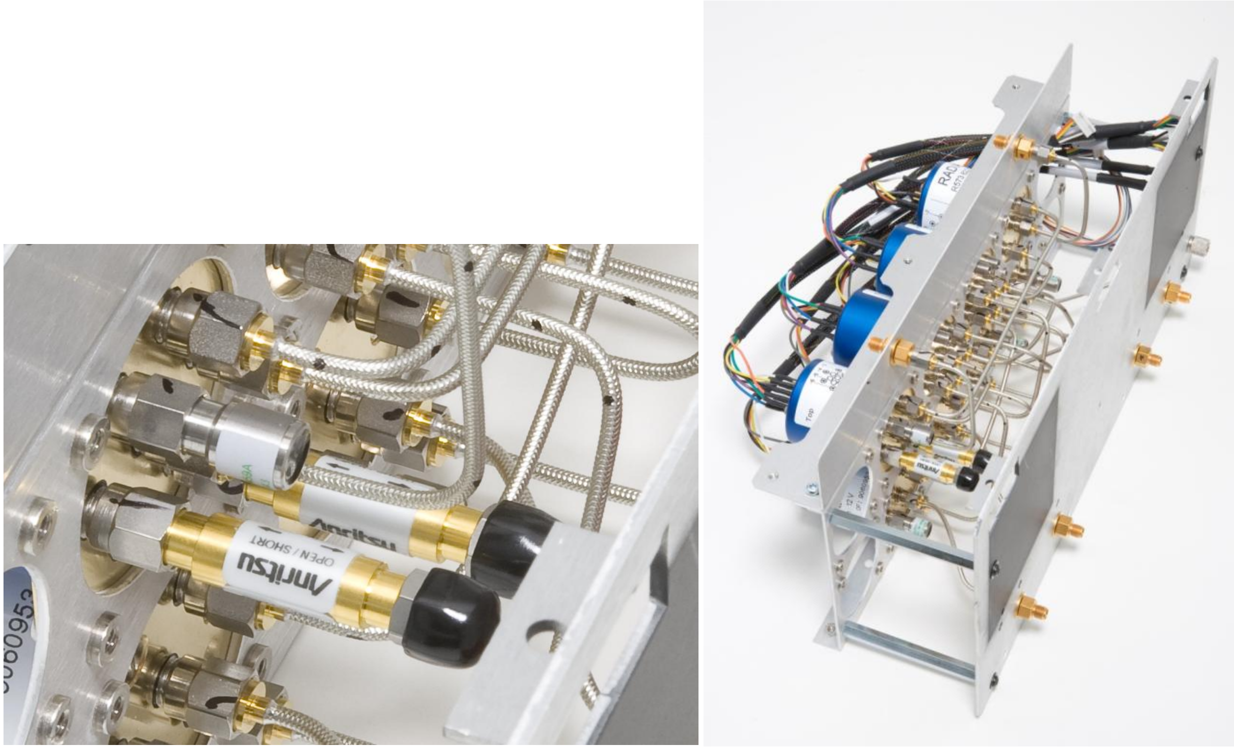


Figure 14: Internal calibration; open,short, load & thru coaxial standards showing connections to internal switch matrix assembly. The RHS image shows the external 4 ports with, 2.92 mm, connectors for attachment to the DUT

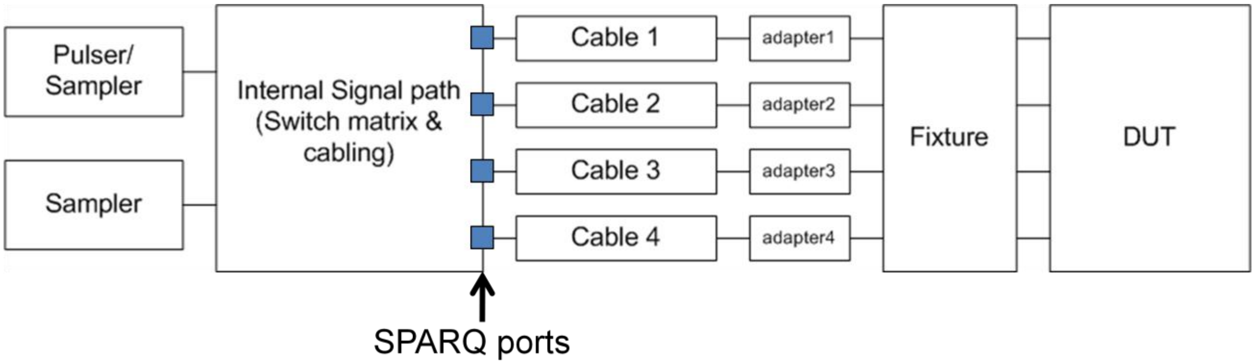


Figure 15: The Sparq system view map. Sparq internal components on the LHS include the pulser/sampler, a second sampler for TDT and the internal switch matrix with cabling to the internal standards kit

Dynamics range vs Frequency

The Sparq operates in three modes; “Preview”, “Normal” & “Extra” to trade dynamic range verses acquisition and analysis processing time. Each mode offers an increasing level of performance with an additional 10 dB of dynamic range, but at the expence of longer processing time. In “Normal” mode typically it can achieve 50 dB dynamic range at 40 GHz. It is expected that user would setup with the “Preview” mode, to check port numbering and physical connections are sound and then proceed to “Normal” mode to acquire higher quality data. When increased dynamic range is required, perhaps for input into a simulation program, “Extra” mode can then be used, figure 16. The fact that the instrument is fully automatic, including all calibration, means that the increased time is not a significant barrier, because the equipment can be left unattended to complete its measurement. For more information of dynamic range see reference[5].

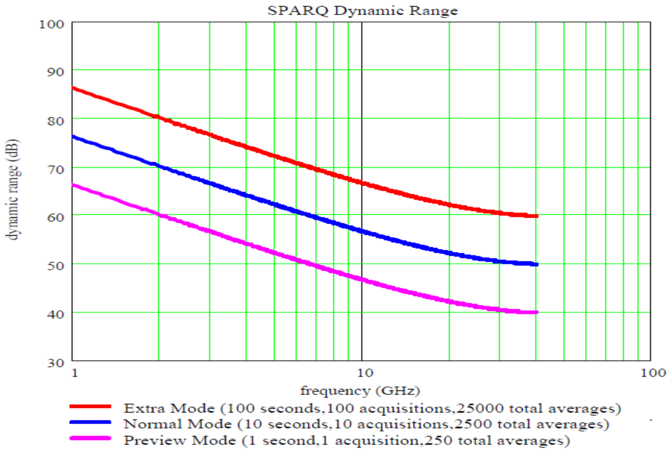


Figure 16: Sparq dynamic range in its 3 modes of operation compared to frequency

Corrleation with Sparq vs VNA S-parameter data

A comparison was made between a two port 40 GHz Anritsu VNA and a 4 port Sparq (using only 2 ports) and good agreement was found within the limitations of the instruments dynamic range, previously discussed, figure 17.

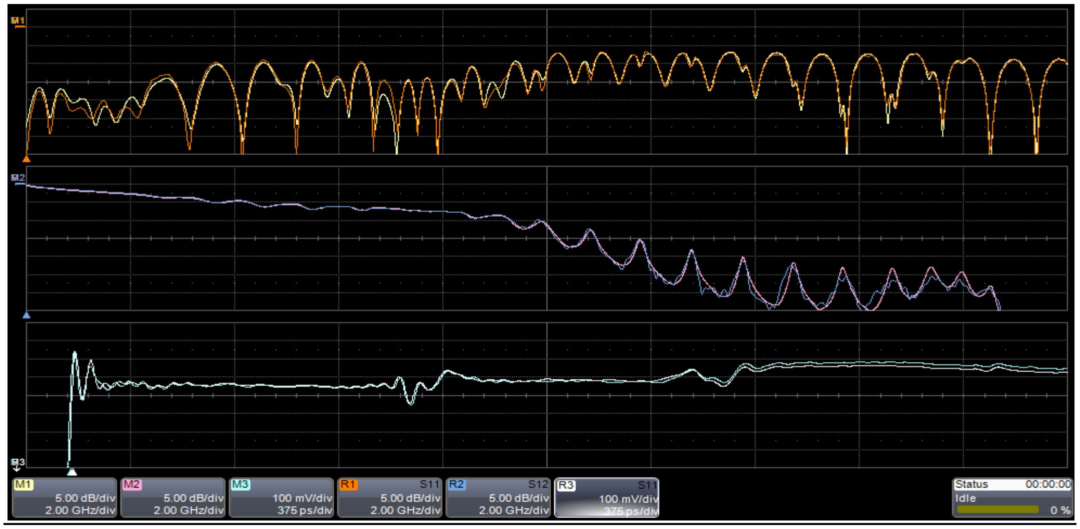
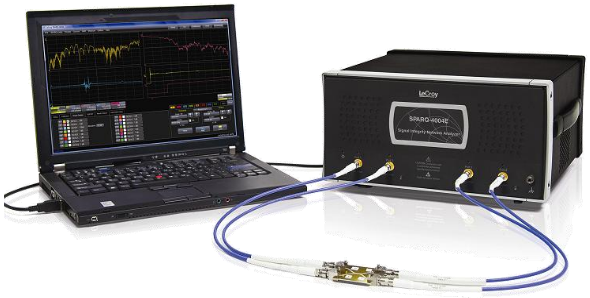


Figure 17: Sparq compared to 40 GHz VNA 2 port measurement; top trace S11, middle S12 and step response below

Summary

The SPARQ, which stands for “S-Parameters Quick”, is a new class of instrument for signal integrity measurement, utilizing up to 12 ports for S-parameter measurement. It is a TDR/TDT-based network analyzer that measures 40GHz, 4port S-parameters with a single button press and at a fraction of a cost of a VNA. Fully calibrated measurements can be made in minutes, and without any need to connect or disconnect cables to external calibration kit standards or electronic calibration modules. S-parameters are provided simulation ready, which is essential for backplane design, with built-in passivity, reciprocity and causality enforcement, and also with a DC reference point (not available on VNA’s). Both Frequency and Time Domain Views are available (Step response, impulse response, Z and Rho), with both Single-ended and Mixed-Mode S-parameter results included as standard. Automatic De-embedding to DUT is also included.



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4 Peter J. Pupalaikis, LeCroy Corporation, “Wavelet Denoising For TDR Dynamic Range Improvement”, Santa Clara, CA, DesignCon 2011

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