LeCroy SPARQ S-Parameter Measurement Methodology

TECHNICAL BRIEF

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Summary

The SPARQ Signal Integrity Network Analyzer uses TDR and TDT to characterize a network's electrical behavior. The process to measure S-parameters includes 3 phases: 1) OSLT calibration, 2) DUT measurement, and 3) S-parameter calculation. 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 using an internal switch matrix assembly that routes signals to internally connected calibration standards and to the front panel ports. "M" models are calibrated with a user's external OSLT calibration kit.

Waveform Acquisition System

In the OSLT Calibration and DUT Measurement phases, the SPARQ acquires waveforms from the TDR and TDT sampler modules using LeCroy's Coherent Interleaved Timebase (CIS) and a 14-bit ADC that routes samples to an FPGA at approximately 10MHz. Either 250, 2500 or 25,000 CIS waveforms are averaged at each step in the OSLT and DUT measurement sequence. The choice is user-selectable via the "Accuracy" selection in the Setup dialog, which also includes a setting for a custom number of averages. 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 the PC running the SPARQ application.

OSLT Calibration Phase

"E" model SPARQ units (Automatic Internal Calibration):

"E" model SPARQs, including the SPARQ-4004E and SPARQ-4002E, utilize an internal OSLT calibration kit that is permanently attached to the SPARQ's switch matrix assembly. (Manual calibrations can also be performed, as described below.) During an automatic calibration, the TDR pulse is routed via the switch matrix to the open, short, and load standards, and then through a calibrated "thru" to a second sampler. At each of these steps, TDR pulses are issued, and TDR waveforms are acquired as described in the Waveform Acquisition System section of this technical note. 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.

Automatic Calibration Sequence: (see figure 1)

1. Baseline: Connect the TDR sampler to a 50 ohm load (measure with TDR pulse off)
2. Open: Connect the TDR sampler to the open standard
3. Short: Connect the TDR sampler to the short standard
4. Load: Connect the TDR sampler to the load standard
5. Thru: Connect the TDR & TDT samplers to the thru standard

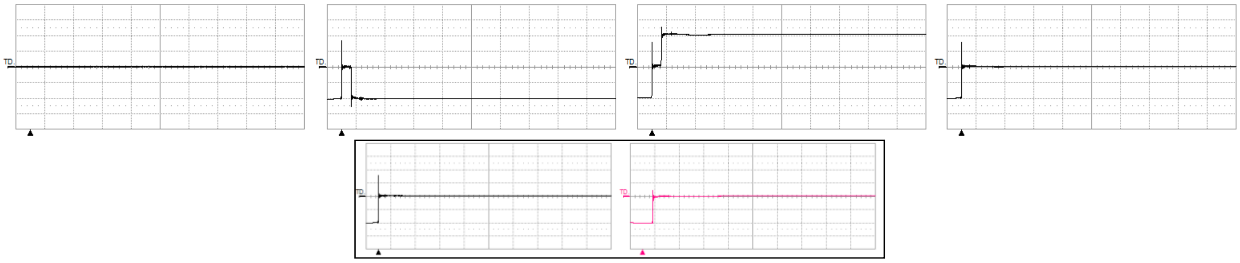

Figure 1: Calibration phase includes baseline correction followed by short, open, load and thru standards. When using an “E” model SPARQ, this phase proceeds automatically by routing the TDR and TDT pulsers to an internally connected calibration kit.

“M” model SPARQ units (Manual-only calibration):

“M" model SPARQs, currently the model SPARQ-4002M, do not include a switch matrix or an internally connected calibration kit. For this model, users perform the OSLT calibration by manually connecting and disconnecting the OSLT standards to the end of the cables connected to the SPARQ. The calibration proceeds via a wizard that prompts the user to attach each calibration kit standard in turn, and acquires TDR and TDT waveforms as described above.

DUT Measurement Phase

During this 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 is no different than when a VNA is used to analyze a network.)

TDR pulses are issued at a rate of either 1 or 5 MHz, depending on the selection for DUT Length mode in the main SPARQ setup screen, and TDR and TDT waveforms are acquired as described in the Waveform Acquisition section of this technical note.

Example DUT Measurement Sequence, 4-port: (See figure 2)

1. TDR: Port 1, TDT: Port 2
2. TDR: Port 2, TDT: Port 1
3. TDR: Port 1, TDT: Port 3
4. TDR: Port 3, TDT: Port 1
5. TDR: Port 1, TDT: Port 4
6. TDR: Port 4, TDT: Port 1
7. TDR: Port 2, TDT: Port 3
8. TDR: Port 3, TDT: Port 2
9. TDR: Port 2, TDT: Port 4
10. TDR: Port 4, TDT: Port 2
11. TDR: Port 3, TDT: Port 4
12. TDR: Port 4, TDT: Port 3

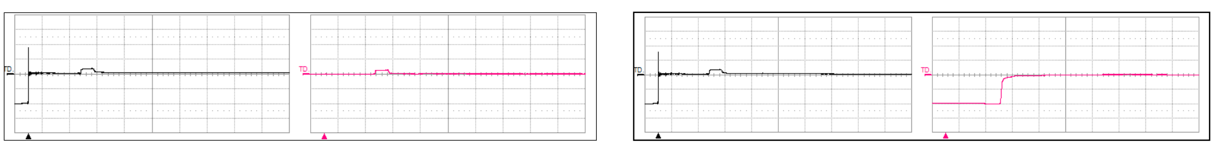

Figure 2: Example TDR (black) and TDT (red) acquisitions. The left image shows waveforms acquired when connecting TDR to port 1 and TDT to port 2. Here, the TDT waveform is showing crosstalk between ports 1 and 2, which are not directly connected. In the right image, TDT is connected to port 3, and shows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

S-parameter Calculation Phase

The S-parameter calculation phase takes place in the user's PC. Each averaged TDR and TDT waveform acquired in the DUT measurement phase is processed as follows. (See figures 3 and 4). Selections made in the SPARQ main setup dialog determine the number of points and end frequency of the resulting S-parameters.

1. The waveforms are input to a wavelet de-noising algorithm that further eliminates remaining uncorrelated noise. (See DesignCon 2011 paper, "Wavelet Denoising for TDR Dynamic Range Improvement")
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. The Factory 2nd-Tier Calibration is applied on top of the automatic calibration. This calibration is contained within the file [Model]_[Serial]_FactorySecondTierCalibration.L12T, which is stored in the CalData.zip file on the SPARQ's SD memory card, and copied to the user's PC on first launch of the application. 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. If enabled, the User 2nd-Tier Calibration is applied. (See application note, User 2nd-tier Calibration for Cable Fixture De-embedding.)
9. The resulting S-parameters are converted to a new reference impedance if the user has chosen to use a reference impedance other than 50 ohms in the extended view of the main setup dialog. This is done via software.
10. The resulting S-parameters are adapted as per the configuration selected in the Advanced Port Configuration window. (This step is performed typically when using mixed-mode S-parameters.)
11. If Gating is enabled, the S-parameters are modified via the gating algorithm, which using either port extension or impedance peeling to move the reference plane by a user-settable delay.
12. When causality and/or limiting of the impulse response time is enforced via the checkbox in the advanced view of the main SPARQ setup dialog, the S-parameters are re-calculated after limiting the impulse response waveforms that are derived via an iFFT of each S-parameters. (See technical note, SPARQ S-Parameter Measurements with Impulse Response Time Limiting.)
13. 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.

Note: Users must take care to avoid using the causality enforcement feature incorrectly. If the selections for End Frequency and Num points result in a delta-frequency value that is “big” such that the corresponding impulse response time length is less than twice the time it takes for reflections to die out, then enforcing causality will cause reflections to be neglected, resulting in an incorrect S-parameter measurement.

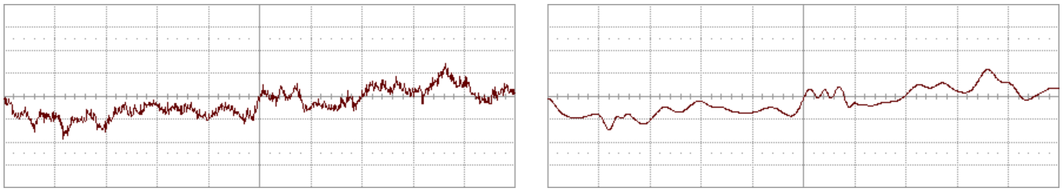

Figure 3: Before (left) and after (right) applying the wavelet denoising algorithm, which provides better than a 10dB improvement to dynamic range.

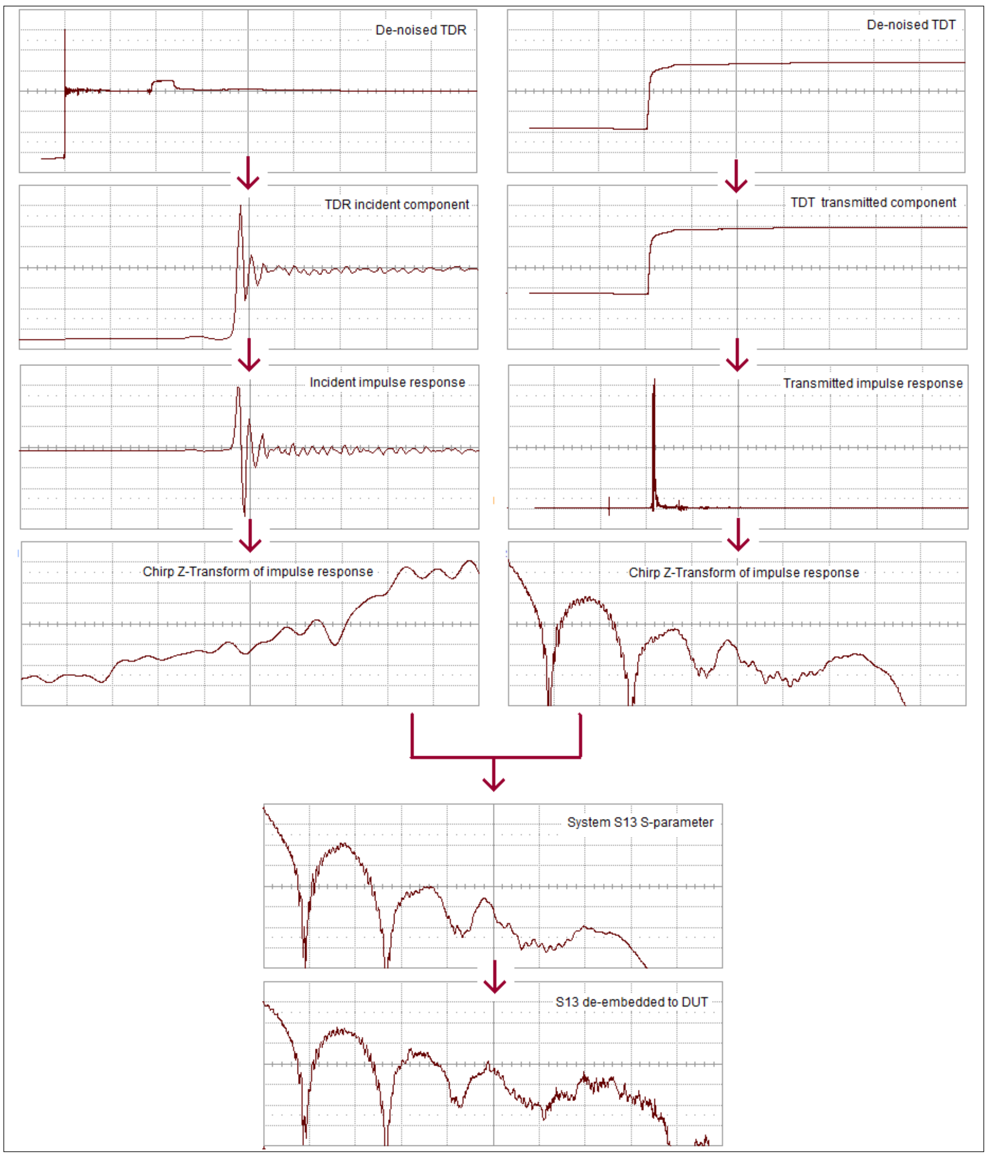

Figure 4: Example illustration of the calculation of the S13 parameter for a DUT where port 1 feeds through to port 3.

Mixed-Mode S-parameters

Users can configure the SPARQ to return mixed-mode S-parameters via versatile configuration screen. In figure 5, the screen is configured to consider ports 1&2 and 3&4 as differential ports, and the S-Matrix is organized in a standard mixed-mode configuration, with SDDij S-parameters in the upper left quadrant and SCCij in the lower right. The user has the ability to renumber and re-order the ports with this dialog.

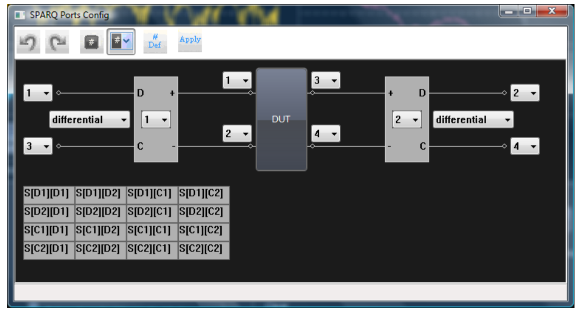

Figure 5: Configuration screen to setup mixed-mode S-parameters

Time-Domain Results

In addition to displaying S-parameter magnitude and/or phase, users can choose to view time-domain results including step response, impulse response, rho and Z. These are calculated from an S-parameter by performing an inverse FFT on the measured S-parameters to obtain the impulse response, and then by convolving with a user-definable impulse. The impulse's integral is a raised-cosine step function with risetime configured in the user interface.

Result Display

Users can view up to 16 result waveforms, along with S-parameter results that are imported from file for comparison purposes.

Figure 6: SPARQ application displaying mixed-mode S-parameters and associated time-domain responses.