DesignCon 2015

Hybrid Modeled Measured Characterization of a 320 Gbit/s Backplane System

Josiah Bartlett, Tektronix
Josiah.Bartlett@Tektronix.com

Sarah Boen Vo, Tektronix
Sarah.Boen@Tektronix.com

Ed Ford, Tektronix
Ed.Ford@Tektronix.com

Abstract

A classic problem signal integrity engineers face is measuring and simulating a high speed, complex SERDES system accurately- often the two are at odds instead of coherent. This paper explores a case study of a multilane Ethernet backplane 320 Gbit/s system that is difficult to fully measure and deembed, implements a hybrid method of modeling, deembedding, and measurement, explores improvements to the metrology and independent verification of results, and discusses the methodology both at 28Gb/s and 10Gb/s. The raw, deembedded, and probed measurements of an active channel versus simulations are examined pathologically for increased confidence in metrology and simulation.

Author(s) Biography

Josiah Bartlett is a Principal Engineer in the Probes group of Time Domain Business Unit at Tektronix. He has 17 years of experience as an analog/mixed signal designer, signal integrity, metrology, and electromagnetic simulation expert. He has an MS from Oregon State University and a BSEE from Washington State University.

Sarah Boen-Vo is a Product Marketing Professional, specializing in High Speed Serial Applications at Tektronix. She has worked at Tektronix in various roles for over 15 years. These roles have included Product Marketing Manager, Product Planner, Program Manager, and Software Design Engineer. Sarah is currently working on analysis solutions, including Jitter and Link Analysis. She has a MBA and BSCS from the University of Portland.

Ed Ford is a Senior Account Manager based in Austin, TX. He has worked at Tektronix in various roles for over 36 years. These roles have included 10 years of Manufacturing Test Engineering experience, and Sales and Major Account Management for over 25 years.

Introduction

As serial communication channels scale up to multiple lanes and faster bit rates, measuring systems to ensure compliance becomes increasingly complicated. Devices such as transmitters need to be verified to the package level, by measurement on a physical system. Probing directly at the measurement point in many cases is not feasible and requires post-processing to remove the effects of the channel (deembed) between the measurement point and test equipment. Often measuring and deembedding the channel involves obtaining a very large port count S parameter block to account for crosstalk and inter-lane skew. Calibrating instrumentation and probing a multi-lane channel is a multi-day endeavor that is prone to error. In the case of a 32 lane system, 64 traces must be characterized and deembedded- an arduous task any way you chose to do it. Often, the channel includes packages, connectors, and other structures that don’t cascade well from separate measurements, so modeling is the only way to truly deembed the channel. This paper postulates that a combination of channel simulation and measurement can be used to accurately deembed measurements of a full system channel, removing the need to take extremely complicated measurements and reducing the most tedious part of the process. The process becomes ever more difficult as edge rates scale past 28Gb/s, as test equipment becomes more expensive, difficult to use, and less mainstream, and higher frequencies require more precision.

Measurement and Removal of Channel Effects (Deembedding)

Characterizing the Channel

The test platform for the paper is shown in Figure 1. It is a large circuit board containing a BGA field, 32 differential traces (top and bottom), high density coaxial test connectors, and adapter cables to connect to 2.92mm equipment.

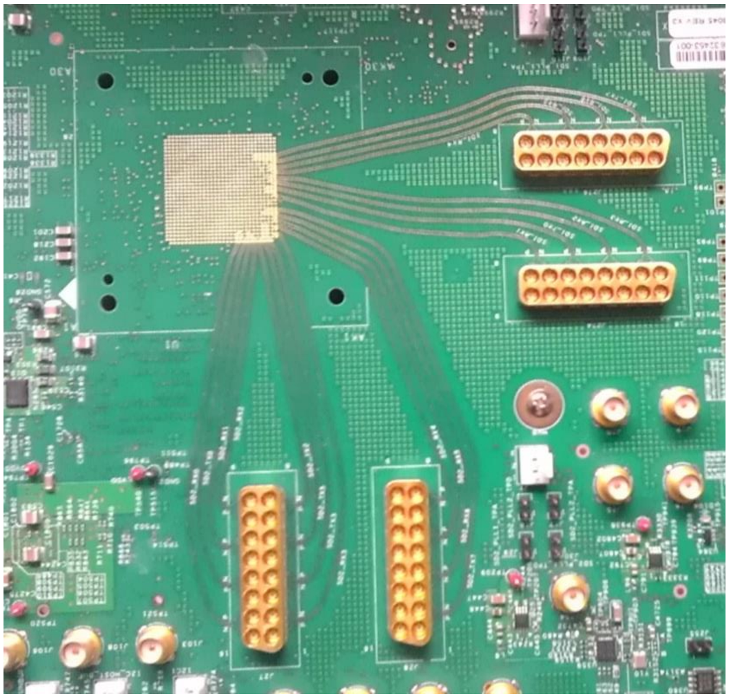

Figure 1: 32 Channel Serdes Test Platform

The test platform shown is used to qualify 10Gb/s multilane Serdes devices on a large IC. While the signal integrity of the test platform is intended to be somewhat better than a typical production backplane, it still has some intra- and interlane skew, crosstalk, and insertion and return loss issues that require careful measurement and deembedding to get the measured signals referenced back to the transmitter device. The reference plane for all measurements is at the circuit board pads where the package is soldered down. The channels to be characterized and deembedded consist of the balls, vias, traces, test connectors, and 2.92mm adapter cables, as well as any interconnect cable or test leads to the instrumentation. Figure 5 shows a block diagram of the measurement and deembedding of the eye diagram of a pair of channel lanes.

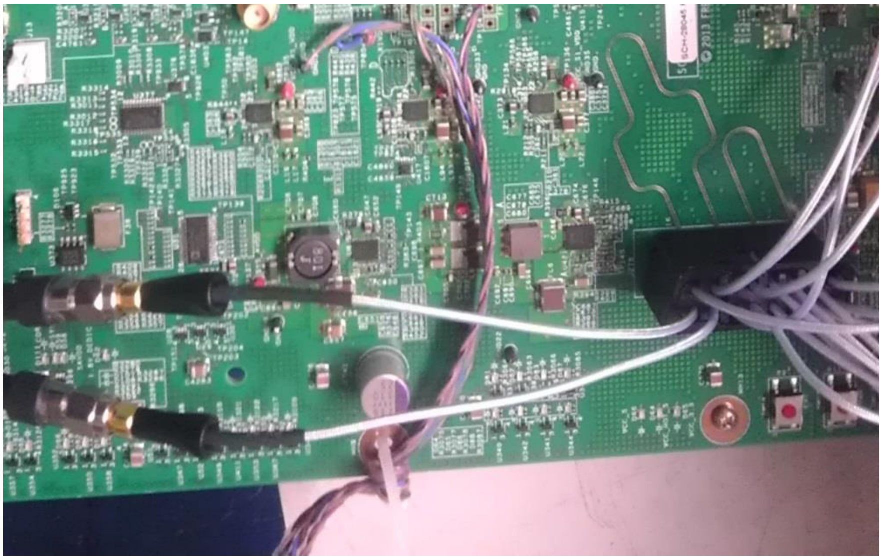

Figure 2: 2.92mm to High Density Test Adapter and Characterization Traces

Obtaining the Channel Behavior Measurements

To obtain the Scattering parameters (S parameters) for each lane of the channel, we can carefully probe the BGA pads on the circuit board with 50 ohm microwave probes. The probes chosen for this device were Ground-Signal 800um pitch probes with 2.92mm connectors. The probes and positioners are shown in Figure 3, along with a probe calibration reference substrate.

Not all signal pairs can easily be probed at the BGA pad, due to signal to GND pin configuration and spacing. Figure 4 shows a partial pinout of the SERDES device. The only viable signal ground is S2GND, which is not immediately adjacent to all of the signal pads, which would require a 1600um or wider pitched probe to accommodate. Wide pitch probes have poor return loss at high frequency which leads to error within the passband of the SERDES device, so care must be taken if these measurements are used for deembed.

Furthermore, obstacles exist on the circuit board- including the test port connector at the other end of the trace. The probes and positioners must be able to clear these obstacles to make contact with the circuit board.

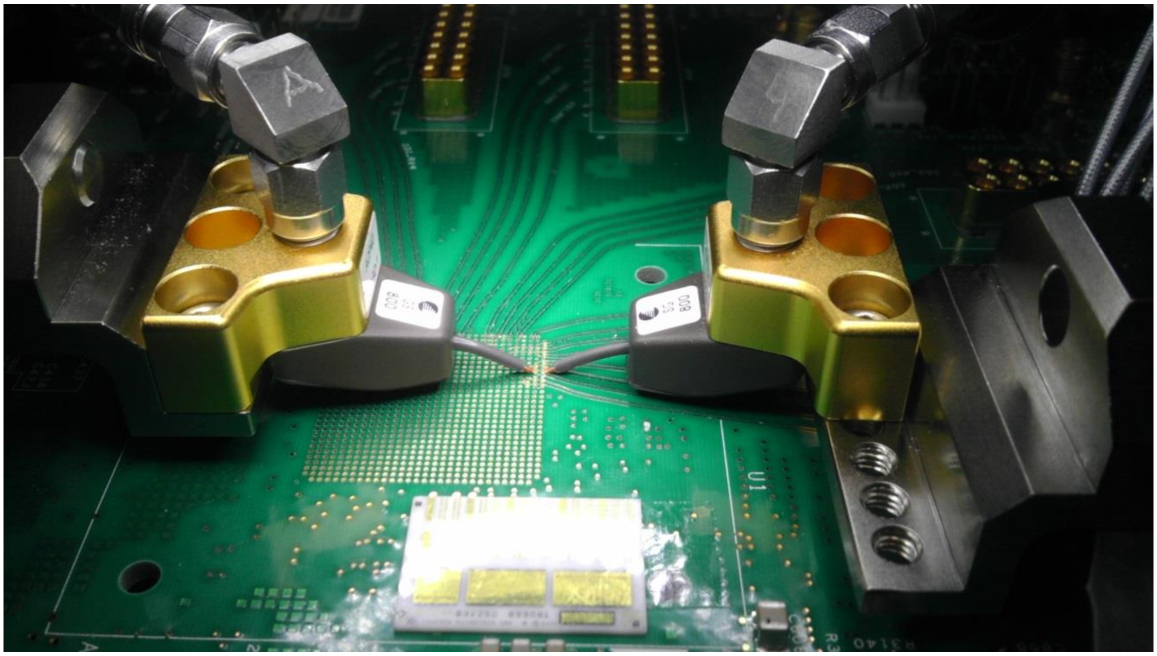

Figure 3: Probing BGA Pads to determine Trace S parameters. Calibration substrate in foreground.

AA	X2GND	X2GND	SD2_RX0_P	SD2_RX0_N	X2GND	X2GND	X2GND
AB	SD2_TX0_N	SD2_TX0_P	S2GND	S2GND	SD2_TX1_P	SD2_TX1_N	S2GND
AC	S2GND	S2GND	SD2_RX1_P	SD2_RX1_N	S2GND	S2GND	SD2_PLL1_TPA
AD	SD2_RX2_P	SD2_RX2_N	S2GND	S2GND	SD2_REF_CLK1_N	SD2_REF_CLK1_P	S2GND
AE	S2GND	S2GND	X2VDD	X2GND	S2GND	S2GND	X2GND
AF	SD2_TX2_P	SD2_TX2_N	X2GND	X2GND	SD2_TX4_P	SD2_TX5_N	X2GND
AG	X2GND	X2GND	X2VDD	X2GND	SD2_TX4_N	SD2_TX5_P	X2GND
AH	SD2_TX3_P	SD2_TX3_N	S2GND	X2VDD	S2GND	S2GND	X2VDD
AJ	X2GND	X2GND	SD2_RX3_N	S2GND	SD2_RX4_P	SD2_RX5_N	S2GND
AK		S2GND	SD2_RX3_P	S2GND	SD2_RX4_N	SD2_RX5_P	S2GND

Figure 4: Partial DUT Package Pinout

Finally, assembly of multiport S parameter data sets from multiple measurements requires unmeasured ports to be terminated to Z0, which is also impractical on many of the traces due to the number of probes that would need to be applied to the package landing area. Also, the return current from the package is usually spread out across multiple pins and power supplies, which can only be fully captured through accurate modeling. Therefore, the most complete and coherent deembed model for the 64 traces that make up the channel of this system has to be obtained through simulations correlated with measurements, ideally both of the measured S parameters of the system and measurements of the device in operation at the transmitter package through an oscilloscope probe.

Deembedding the Channel

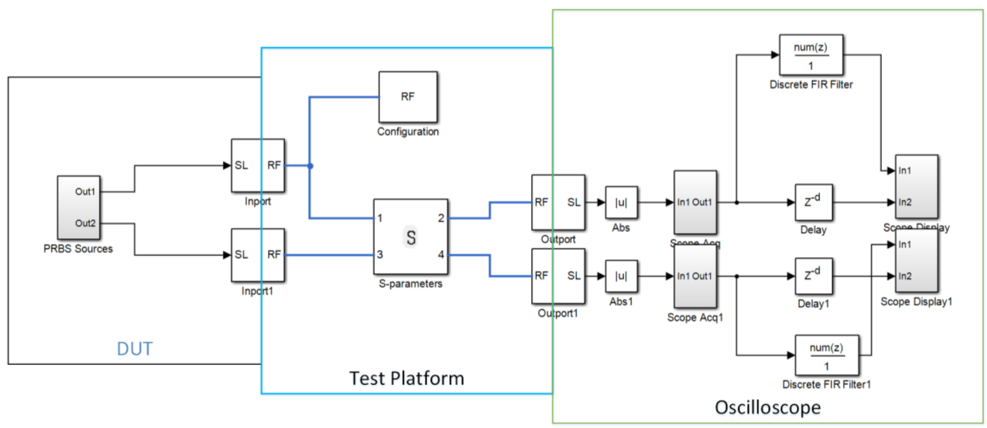

Figure 5: Multilane Measurement and Deembedding

A block model of the eye capture system is shown in figure 5. The diagram represents either a single or adjacent channels of a transmitter (PRBS source), channel (“S” block), Oscilloscope Acquisition, and post-acquisition processing. During post-processing a FIR channel correction filter, is applied to the channel acquisition to deembed the effects of the S block, and a delay block of the same length as the filter is applied to the raw data of the channel to provide a side-by-side comparison of the raw and deembedded data. The FIR filter is obtained by processing the S parameters obtained in the channel behavior measurements, applying a band limiting filter to avoid excessive amplification of noise, and generating a time domain finite impulse response filter used to amplify the portions of the signal that were attenuated by the channel. The step response of a deembed filter for one of the channels in the example is shown in Figure 6.

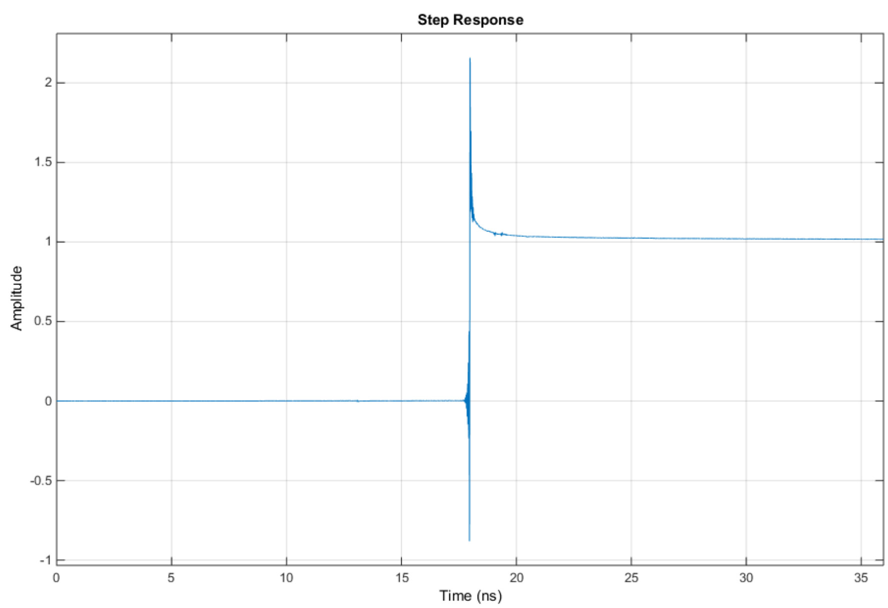

Figure 6: Step Response of Channel Deembed Filter

Effects of Instrumentation Noise on Eye Results

Real world instrumentation has very real noise and distortion, which should not be ignored when doing high speed device characterization. Understanding the effects of measurement noise, frequency and time response, and accuracy is very important to the metrology of device qualification. The interaction of these non-idealities with the device under test is not easy to simply discern off a specification sheet, so in this section we will explore how to determine the instrumentation effects.

In Figure 7, we have taken the S parameters of one of our long test traces, generated a FIR channel correction filter with the SDLA application on our oscilloscope, and simulated the eye diagrams that result from running a PRBS-7 source through the S parameters of the trace. We have sampled all acquisitions at 100GS/s, and we have simulated the acquisition with an 8 bit real-time scope and a 12 bit equivalent time scope. The simulation of the oscilloscope acquisition was done by adding vertical system white and quantization noise taken from the data sheet of a typical commercially available instrument. We have assumed ideal return loss of both PRBS-7 source and receiver. The FIR correction filter was band limited to 30 GHz and the frequency response is shown in Figure 27. It boosts about 10dB at 20 GHz to cover the loss of the channel, which is shown in Figure 7.

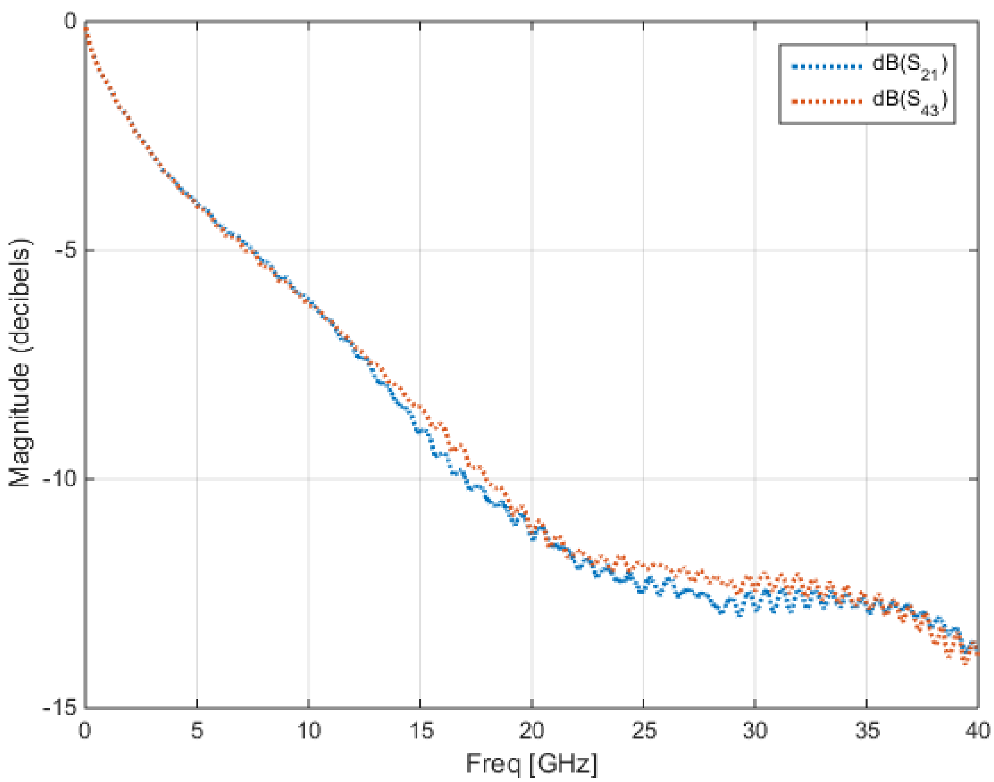

Figure 7: Channel insertion loss for test trace pair

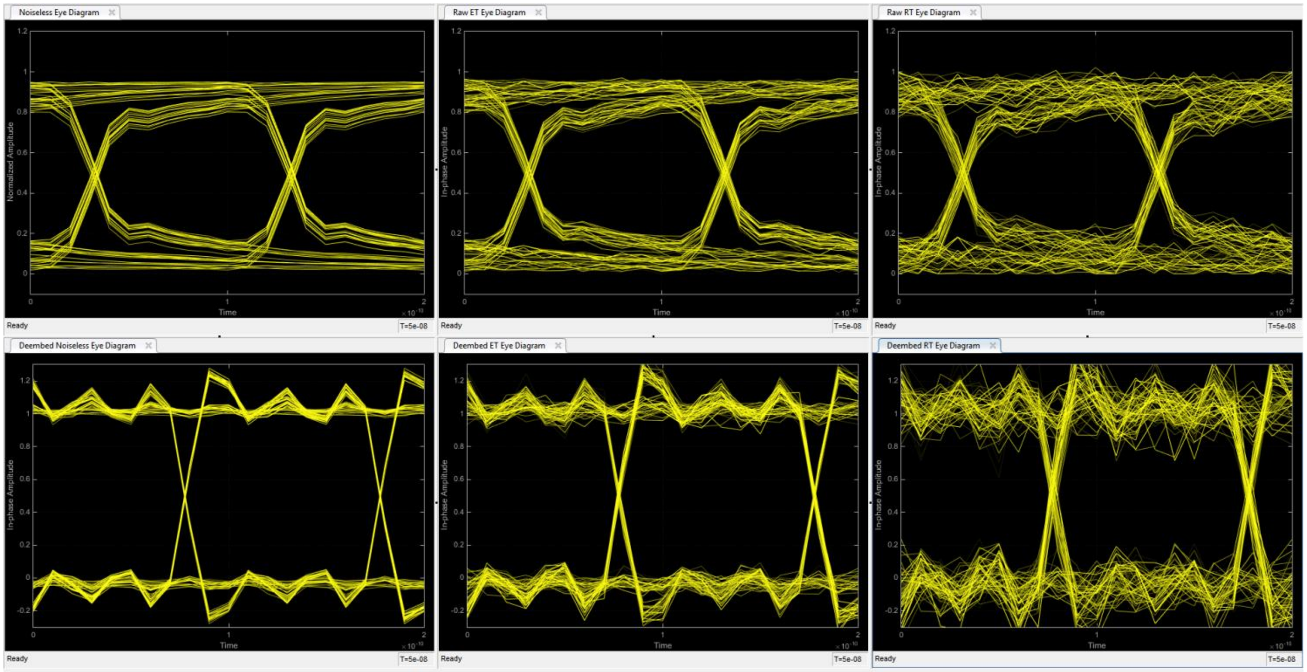

Figure 8: Eye Diagrams of Lossy Channel.
TL of Channel; TC of Channel Measured with ET scope; TR of Channel Measured with RT Scope;
BL of Deembedded Channel; BC of ET Deembedded Channel; BR of RT Deembedded Channel

In Figure 8, we see, from top left to top right, the simulated raw eye diagram taken at the receiving end of the trace with a perfect 100GS/s scope, then in the center with a 100 GS/s 12 bit low noise equivalent time scope, then on the right with a single-shot acquisition on a real-time scope. The raw waveforms show increasing noise but similar jitter and eye openings. However, when we apply the deembed filter, the differences are more stark.

The equivalent time scope shows slight degradation to the eye opening and timing jitter, but the real time scope still shows significant jitter and a closed eye. The deembed filter is shaping the step response of the signal, but also amplifying vertical noise of the scope's acquisition system. Since we are boosting nearly 15 dB at the bandwidth of the scope, that noise can be significant. This illustrates the need to choose our channel design, instrumentation, and measurements carefully to be able to separate transmitter or receiver problems from the noise of the channel. Fortunately, all is not lost. The example shown is somewhat of an extreme case. A 10Gb/s system has very little energy at 30 GHz, and most of the information needed can be extracted with a lower deembedding bandwidth, thus minimizing noise amplification as shown later in the paper. There are other reasons to choose certain equipment. A real-time scope can capture glitches and other non-repetitive behavior in a system that other instrumentation cannot.

Effects of Channel Measurement Inaccuracy on Eye Results

Another common source of error in channel measurements is inaccuracy of the information used to deembed the channel. Accurate broadband S parameter measurements and simulation can be rather difficult, especially for complex systems. Inaccurate measurements, for example under or over estimating insertion loss, can result in deembedded eye diagrams that visually look okay, but have eye openings that are far smaller than acceptable even though the jitter numbers are fairly similar. The example below illustrates that an under-deembedded trace shows very similar jitter and eye width results, but the eye opening is inaccurate. For a transmitter with an eye height spec, under or over estimating the loss of a trace can result in low yield or overconfidence in the design.

The designer of the system used in this example originally characterized a test trace on the circuit board, and came up with deembed model A (data which stops at 20 GHz in Figure 9). The designer also cut the trace and measured the transmitter output with a real-time scope probe, and found a fairly large discrepancy between the two measurements. Re-measurement of the trace on another instrument reveals that the trace insertion loss is worse than originally measured, and the authors generated deembed model B.

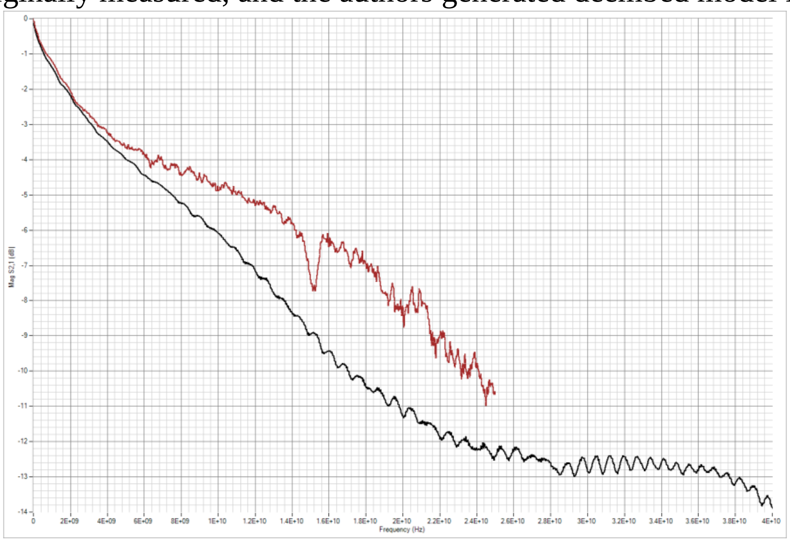

Figure 9: Deembed Model A (too little loss) versus Model B (correct loss)

In addition, the insertion loss and electrical length of the traces on the system circuit board do not match each other well enough to use the same deembed filter for all traces. (Figure 10). For this reason, using nominal filter models can lead to incorrect results.

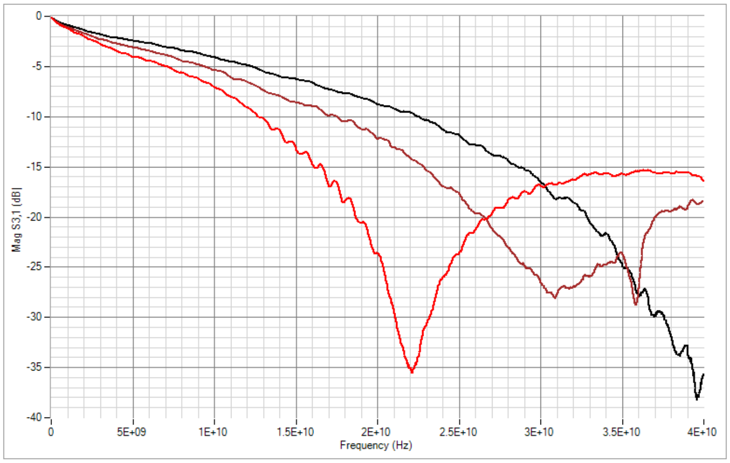

Figure 10: Lane to Lane insertion loss matching

The original eye diagram of the generator is found in Figure 10. Comparison of the two eye diagrams on a real time scope produce the eye diagrams in Figure 12, and the measurement results found in Table 1.

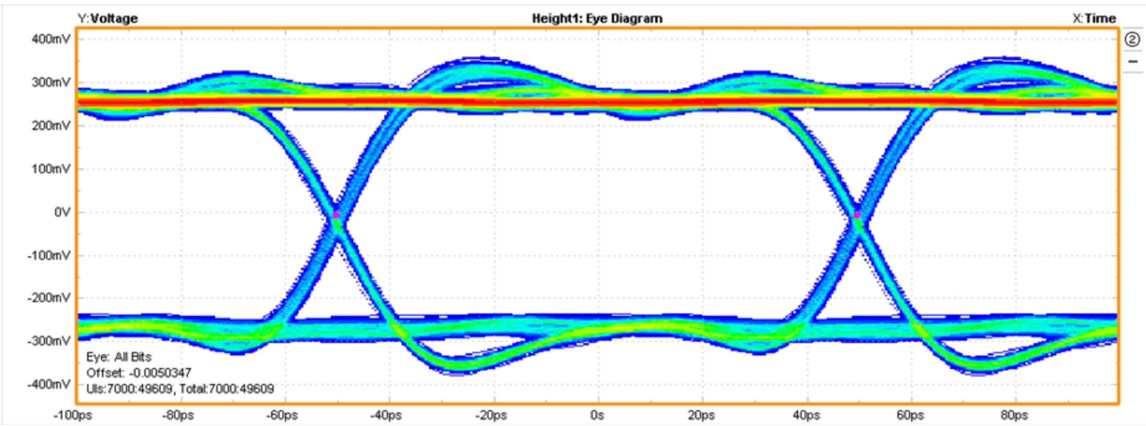

Figure 11: PPG source eye diagram acquired on 30 GHz Real-time scope

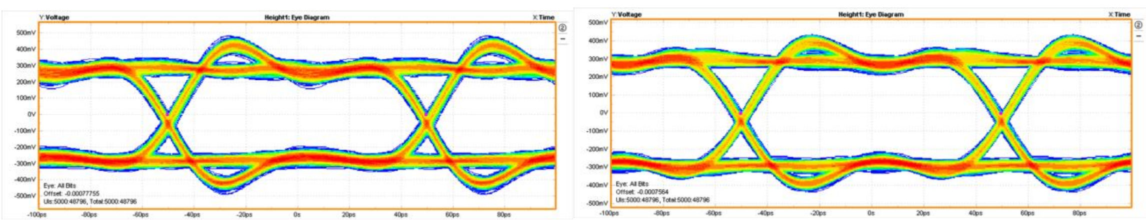

Figure 12: Eye for Trace Deembedded by Model A; Eye for Trace Deembedded by Model B

We have lost 6.8% of the eye height due to noise in the completely deembedded signal with Model B. However, Model A shows an 18.8% loss of eye height due to incorrect gain. This could be enough to trigger a redesign or specification reduction of a transmitter even though it was not warranted.

Measurement	Generator	Incomplete Deembed A	Complete Deembed B
Height1, Tp2 M2	462.88mV	375.93mV	431.24mV
TJ@BER1, Tp2 M2	10.353ps	13.389ps	12.002ps
RJ–dd1, Tp2 M2	529.57fs	403.75fs	311.69fs
DJ–dd1, Tp2 M2	2.9395ps	7.7361ps	7.6380ps
Width@BER1, Tp2 M2	89.647ps	86.611ps	87.998ps

Table 1: Jitter Test Results of Deembedded Trace

Effects of Deembeded Channel Crosstalk on Eye Results

Since this paper is detailing a multilane system, it must discuss the effects of crosstalk on eye results. For illustration purposes, let's choose the most extreme case of a second lane spaced the same trace to trace distance as the differential pair of the same lane. This would result in very heavy crosstalk, but could easily happen on a circuit board that wasn't routed with heavy constraints. We show the insertion loss and near to far end crosstalk S parameters in Figure 13.

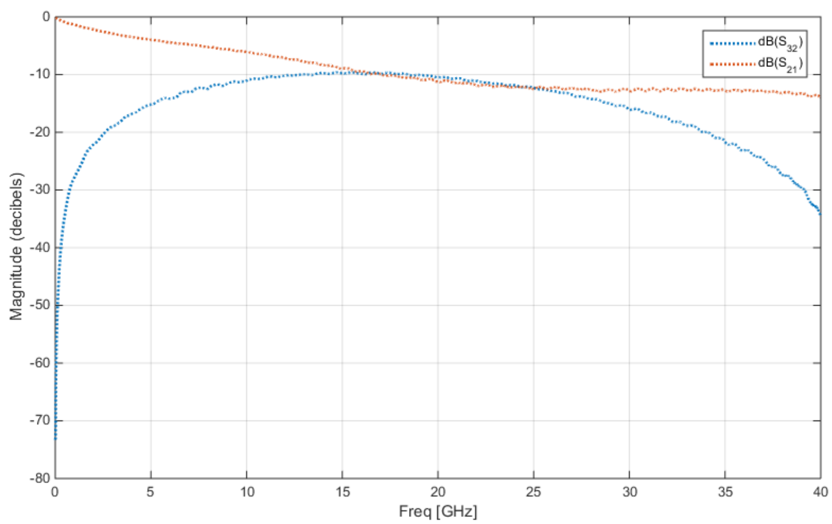

Figure 13: Strong Crosstalk Channel Response

Note that the insertion loss and crosstalk gains actually slightly cross! This means that when we deembed the channel we can get severe eye degradation by amplifying the midband of the signal. We demonstrate that in Figure 14.

Again, we show the simulated raw (top row) and deembedded (bottom row), of signals acquired by, from left to right, an ideal oscilloscope at 100 GS/s, an equivalent time 12 bit oscilloscope at 100 GS/s, and a real-time oscilloscope at 100 GS/s, bandwidth limited to 30 GHz.

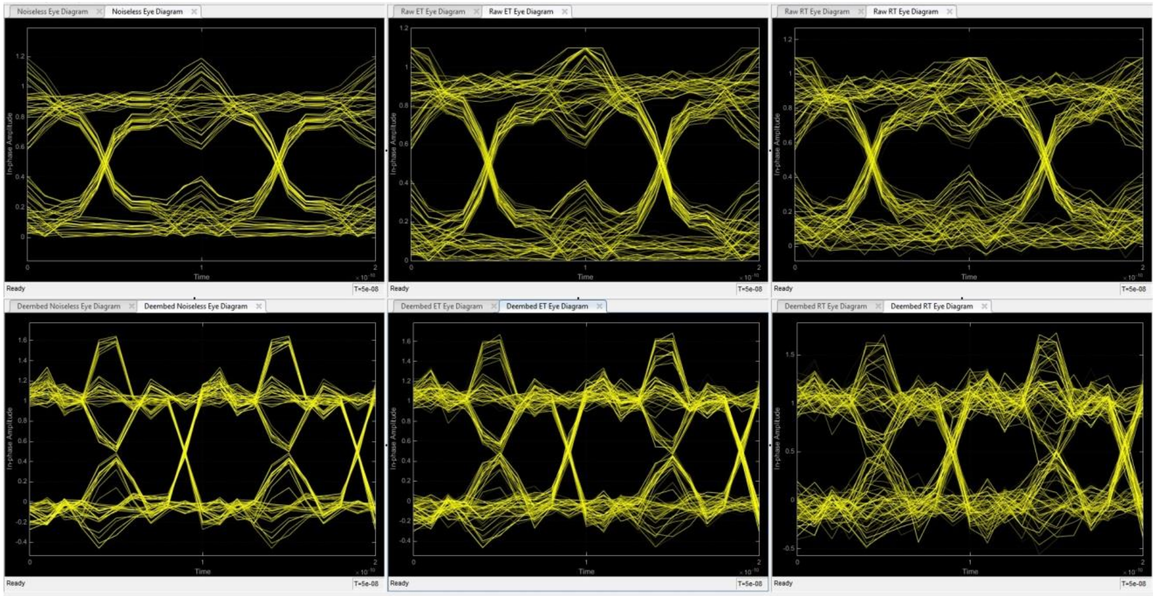

Figure 14: Strong Crosstalk Effects on Deembedded Eye

Deembedding of traces with strong crosstalk leads to closed eye due to deembed filter gain, unless instrument can account for crosstalk signal and selectively deembed with time variant filtering. While this example is almost certainly worst-case, it demonstrates that one needs to be very careful with channel design for characterization.

Probing the Channel

Now that we have done simulations and taken measurements, how do we know which one is correct if discrepancies exist? Increased confidence can be achieved by probing the signal channel and examining the eye closer to the transmitter, either invasively by cutting the trace and placing termination and probe on the circuit board, or by probing on the trace without modification (Figure 15). Both cases change the channel, and require accounting for the effects of the probe and termination changes.

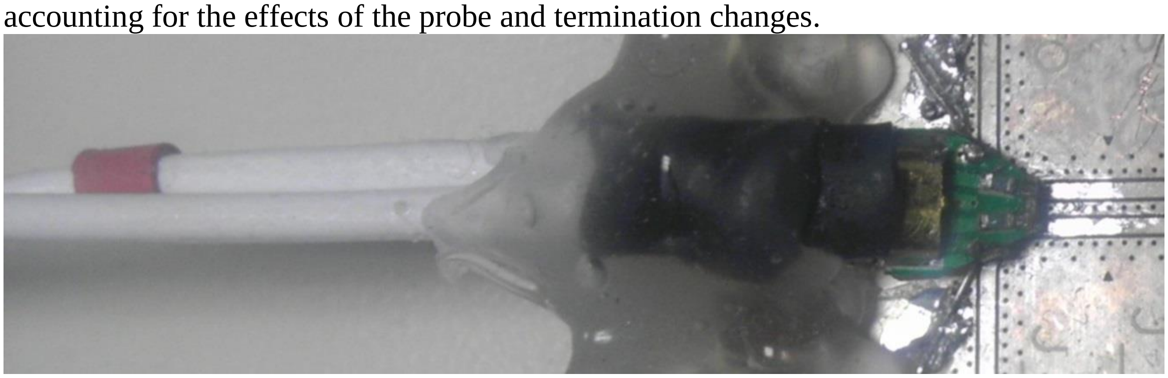

Figure 15: A Soldered 25 GHz Differential Oscilloscope Probe

Fortunately, in a linear system we can account for these changes if we know the input loading of the probe and the acquisition noise is reasonable. Building a deembed filter based on the channel and known probe loading allows us to cancel out the effects of the probe on the eye and compare the probed and unprobed channel results, to better gain confidence in modeled channels. (Figure 16)

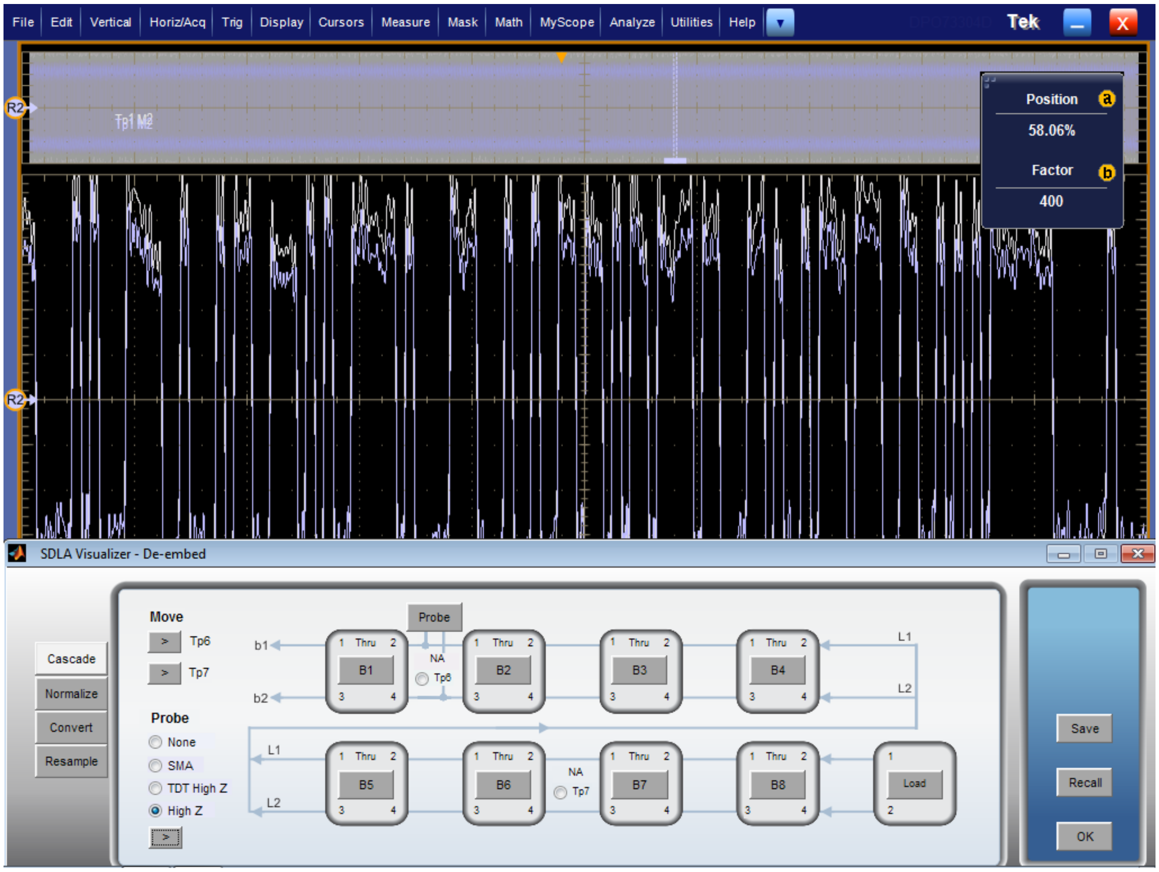

Figure 16: Probe load deembedding on oscilloscope

Modeling the Channel Based on Measurement

After we have made sparse measurements of test traces and channels on the test board, we can start modeling the channel. Models need to be created up to the measurement reference plane or to cables and adapters that can be deembedded in order to compare simulation and measured results. Figure 17 shows modeling of a channel of the circuit board with a layout based simulator, and Figure 18 shows an eye diagram generated by the simulator.

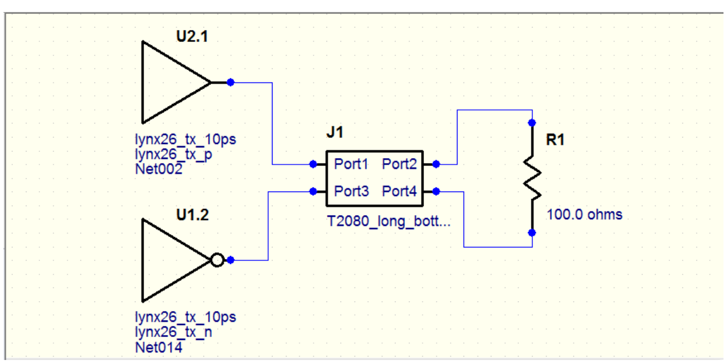

Figure 17: Modeling a lane in a layout simulator

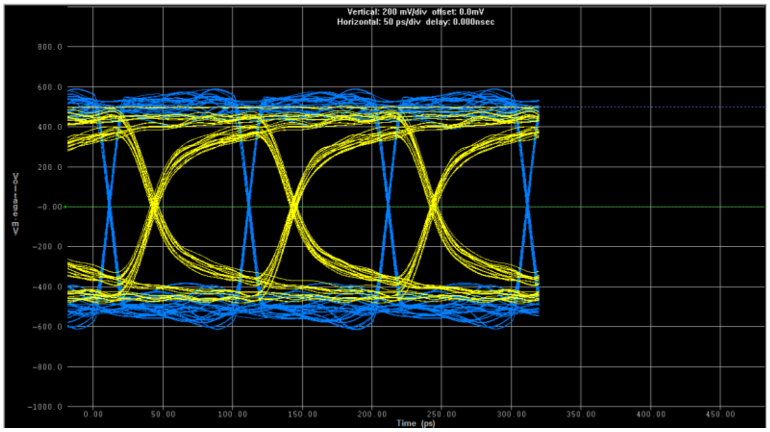

Figure 18: Eye diagram created by layout simulator

Effects of Inaccurate Channel Model

Now, suppose we model a measured channel, using simple coaxial line and microstrip models, without frequency dependent dielectrics (Figure 19).

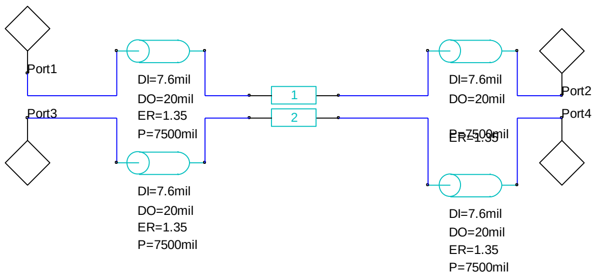

Figure 19: Trace model

If a very simple trace model is generated, the insertion loss may only agree with the measured insertion loss at two points as shown in plot on the left side of Figure 20. The resulting deembed filter, shown on the right side of Figure 20, over-amplifies the high frequency loss, resulting in an eye height reduction due to ringing, but jitter and eye width are not affected very much. (Table 2.)

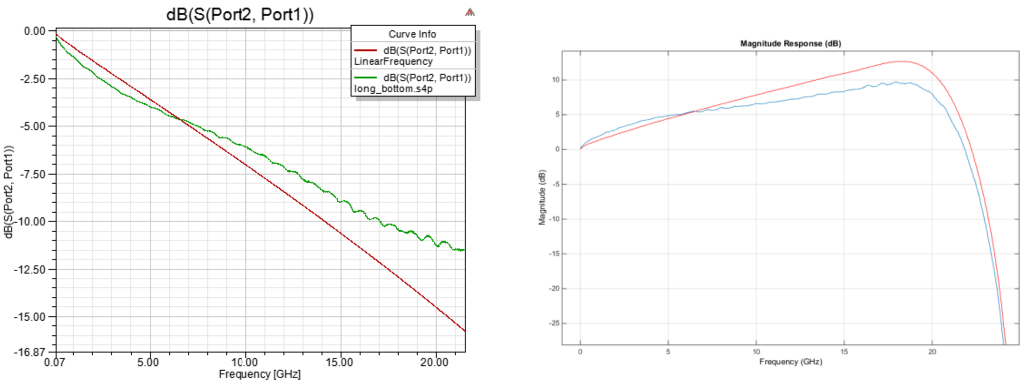

Figure 20: Measured versus Simply Modeled Trace loss and deembed filters

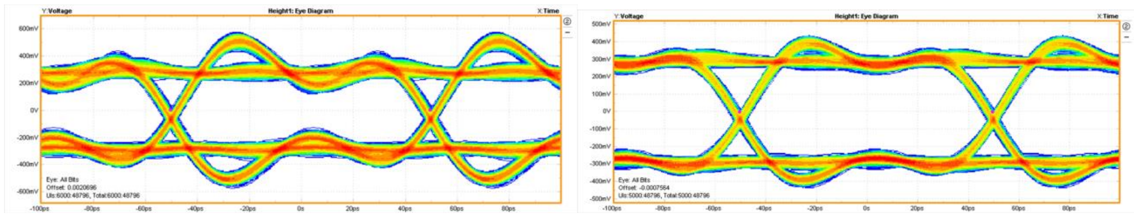

Figure 21: Eye diagrams for Simply Modeled versus Measured Trace

Measurement	Generator	Simulated Deembed A	Measured Deembed B
Height1, Tp2 M2	462.88mV	285.55mV	431.24mV
TJ@BER1, Tp2 M2	10.353ps	12.46ps	12.002ps
RJ–dd1, Tp2 M2	529.57fs	359.58ps	311.69fs
DJ–dd1, Tp2 M2	2.9395ps	7.4269ps	7.6380ps
Width@BER1, Tp2 M2	89.647ps	87.54ps	87.998ps

Table 2: DPOJET measurements of inaccurate simulated trace versus measured trace

Now, if we improve the model, (Figure 22) and use it to deembed the measured trace (Figure 23), we get tighter correlation between the measurement and simulation results as shown in Table 3.

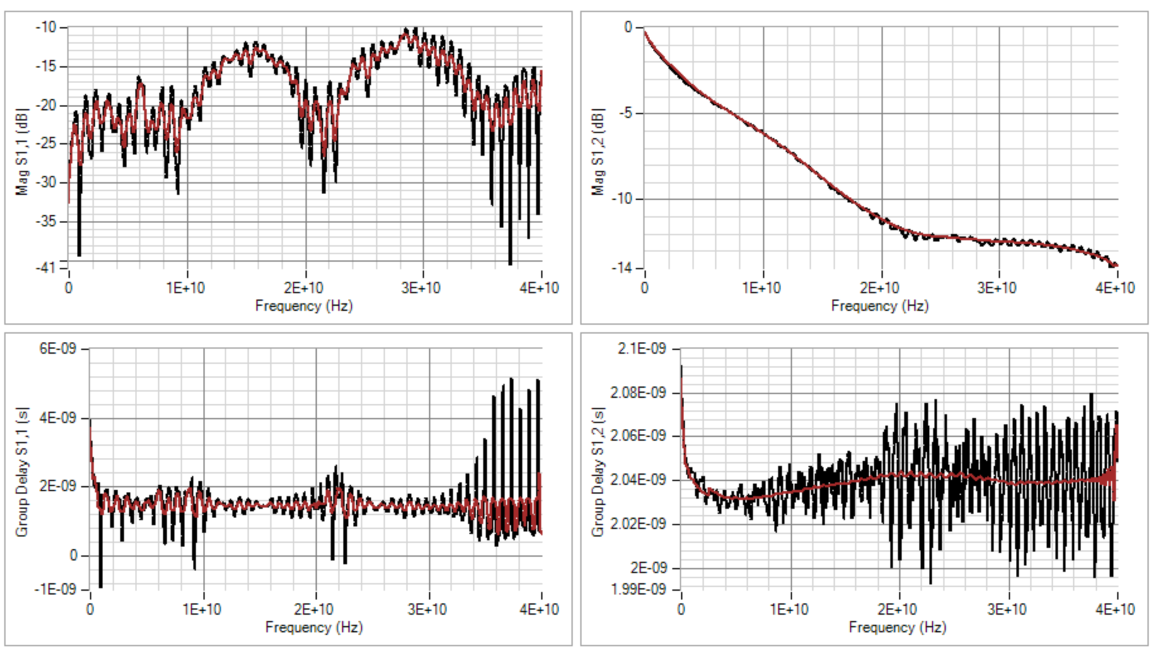

Figure 22: Improved model (smooth red trace) of measured trace (black)

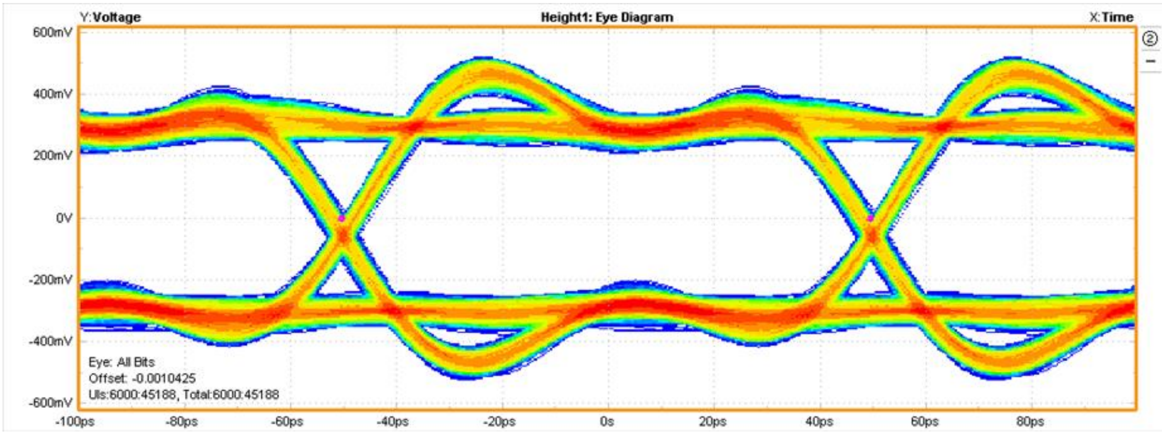

Figure 23: Eye diagram for measured acquisition deembedded by simulated trace

Measurement	Generator	Improved Simulated Deembed A	Measured Deembed B
Height1, Tp2 M2	462.88mV	435.74mV	431.24mV
TJ@BER1, Tp2 M2	10.353ps	12.7ps	12.002ps
RJ–dd1, Tp2 M2	529.57fs	326.91ps	311.69fs
DJ–dd1, Tp2 M2	2.9395ps	8.1275ps	7.6380ps
Width@BER1, Tp2 M2	89.647ps	87.296ps	87.998ps

Table 3: DPOJET measurements of improved simulated trace deembed versus measured trace deembed

The new modeled trace matches the measured trace very well, and results in an eye and jitter measurement that is very well correlated. Modeling the trace with improved accuracy require causal, frequency dependent material models and specific tuning for discontinuities like vias and connector launches. A strong understanding of physical manufacturing process variations and evaluation of prototypes is required to achieve a highly correlated model.

Tips and Tricks Above 10Gb/s

Instrumentation Bandwidth

The 3rd Harmonic of 28G is 42 GHz. Therefore, we need instrumentation and interconnect capable of higher bandwidth and greater accuracy. Figure 21 shows that the measured return and insertion loss of a trace on our test board with a 40 GHz VNA (2.92mm connectors) and a TDR/TDR measurement system using Iconnect software start to diverge at higher frequency due to bandwidth and calibration limitations. One of the reasons these measurements diverge is the high frequency ringing at the adapter between the instrument and the DUT (Figure 24).

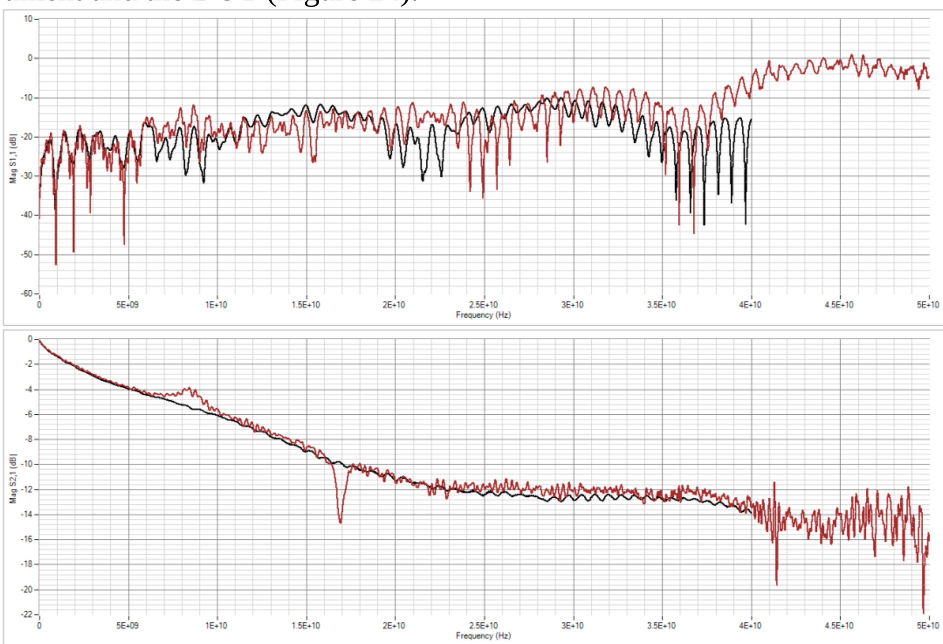

Figure 24: VNA and TDR measurements diverge at higher frequency.

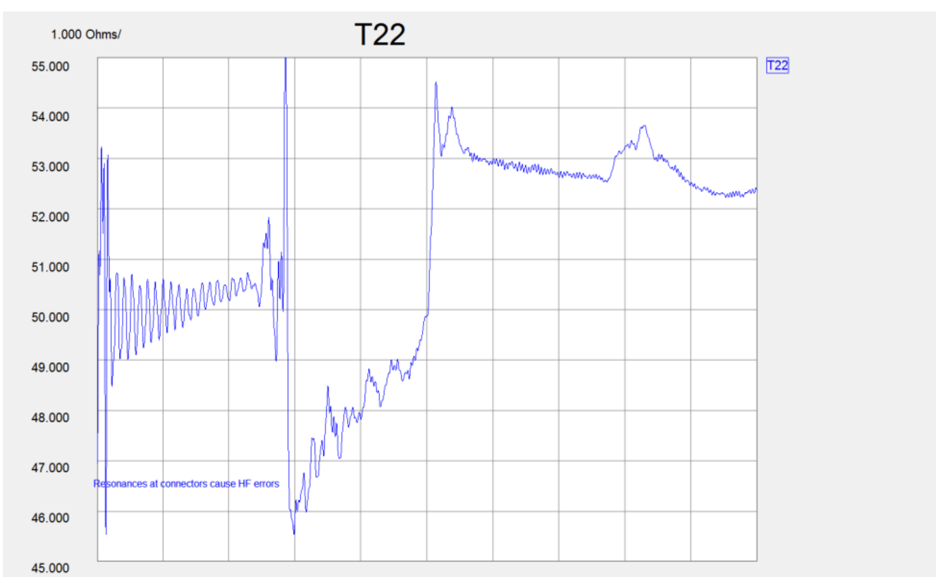

Figure 25: Resonances due to poor connection cause high frequency ringing

Package/Interconnect Measurement

Another similar source of error to adapters are microwave probes. The 800um single ground probes used to measure our 10Gb/s system exhibit modal behavior above approximately 30 GHz (Figure 26), which makes them difficult to calibrate and obtain passive behavior. This is compounded when they are cascaded or deembedded from other measurements.

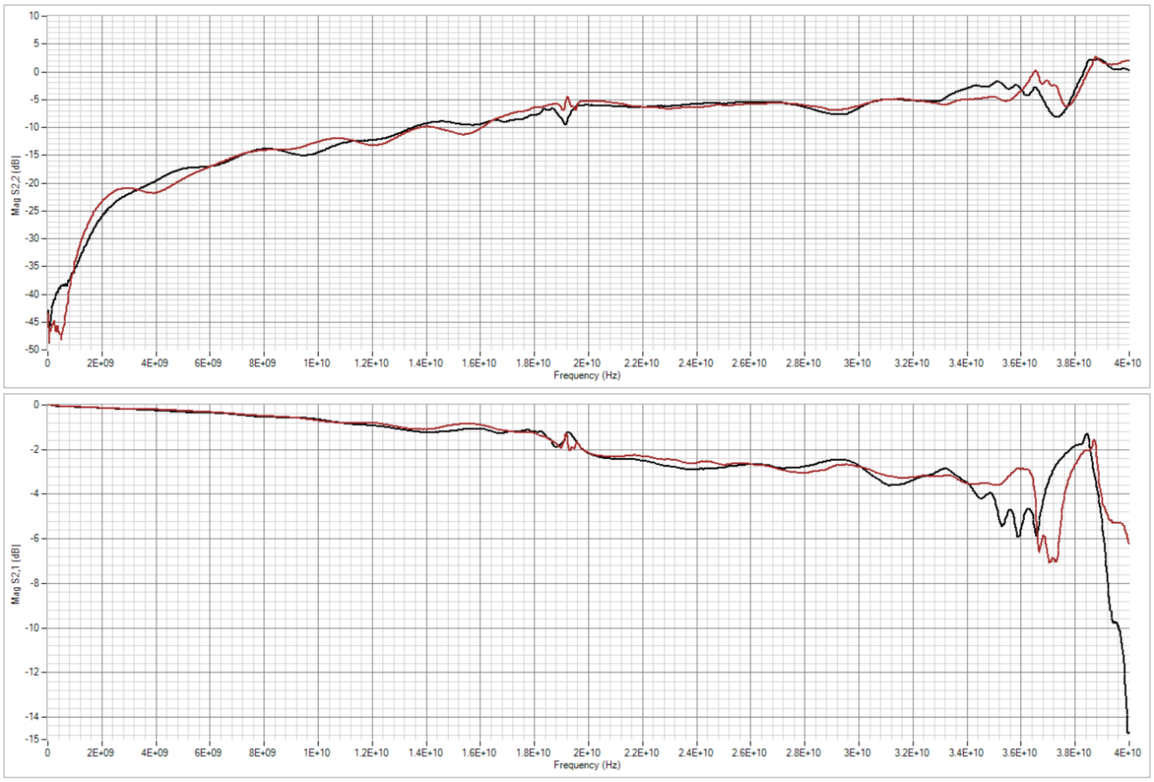

Figure 26: 800um pitch Microwave Probe Calibration is unstable above 30 GHz

Signal Probing

Realtime scopes and probes are improving in bandwidth and loading as time goes on. While physical access to signals is difficult, test platforms should be designed with signal taps or probe points in strategic locations to improve confidence in channel measurement, deembedding, and modeling.

Deembedding

At any signal rate or bandwidth, deembedding appropriately to the instrumentation noise is important, but it becomes more so as instrument bandwidth increases due to integrated noise power. Simple noise studies and comparison of results go a long way to minimizing deembed errors while still capturing important harmonics and other key metrics. (Figure 27). Custom deembed filters can also be built that have unity gain above some cutoff frequency, so they do not amplify noise or signal but still pass harmonics for estimation purposes.

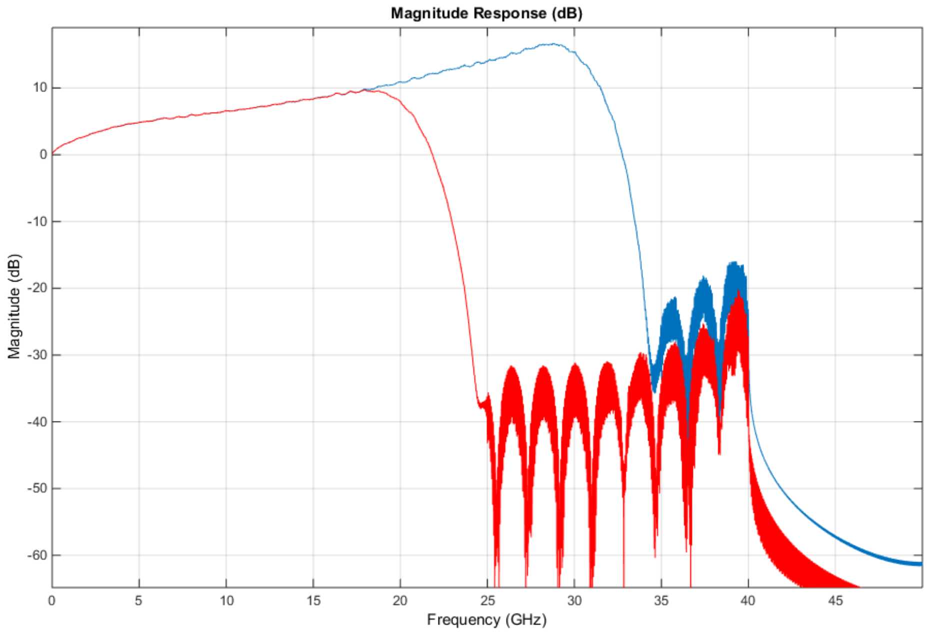

Figure 27: Deembed filter response limited to 20 GHz versus 30 GHz Bandwidth

Conclusion

As data rates increase, the need to remove the effects of the channel to accurately measure the device under test is required. This task is further complicated when the device has multiple lanes as the measurements are not only difficult to perform, but time consuming. It is often necessary to measure a subset of those lanes and build simulation models that match the measurements. Models that can be built for the remaining lanes. This process requires special care to ensure that the measured models are accurate, the simulation models match the measurement, and that the FIR channel correction filter is designed properly. This paper has illustrated that it is possible to build channel simulation models based on actual channel measurements and use those models to accurately de-embed the channel effects to characterize the device under test at the transmitter output.

Special thanks to Freescale for providing the device under test used in this paper.