High Frequency PCB Probing with Fixture Removal for Multi-Port Devices

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We will explore how to provide robust high frequency multi-port measurements of PCB structures.

Modern day printed circuit boards (PCBs) have easily met the challenge of 10 GHz high frequency designs and now push well beyond 40 GHz. Higher complexities of mixed signal devices and increasing densities of sub-millimeter pitch packaging creates a significant multi-port design challenge that is often difficult to verify or troubleshoot with existing measurement calibration techniques. Full characterization of a signal path is easily done with a high frequency Vector Network Analyzer, but making the fixture connection from the large coaxial inputs of a VNA to the planar PCB substrate is not a trivial problem at high frequencies [1]. The presence of crosstalk in the multi-port fixture connections and the issues in designing relevant PCB probe calibration standards can easily create a roadblock to acquiring accurate measurements of a PCB footprint or signal path. This article will explore the use of an optimized probe to PCB interposer technique along with simplified calibrations with de-embedding to provide robust high frequency multi-port measurements of PCB structures.

Even with the best of calibration techniques, one cannot calibrate out a fixture that has losses that exceed the sensitivity of the measurement instrument. Utilizing a commercially available 40 GHz probe to connect to a PCB does not guarantee a full 40 GHz connection. It is important to understand the need for a controlled impedance transition from the probe tip to the planar PCB structure to minimize signal degradation and improve accuracies in calibrating out the fixture. Since the performance of the probe depends on how the connection is made to the PCB it is necessary to create calibration standards that incorporate this same electro-mechanical interface for accurate removal of the fixture effects.

Standard Through-Reflect-Multiple Lines (TRL) techniques have historically been the method of choice for calibration standards on PCB, however, when implementing this in a multi-port system it can become very time consuming and prone to human error [2]. Utilizing adapter removal techniques to individually characterize each of the probes based on one TRL calibration can greatly speed up this task. The end result with S-parameters for each probe fixture enables simple and flexible de-embedding of the fixture effects from the measurement or replacement of damaged probes without repeating a TRL calibration. Newer calibration techniques using 2x through Automatic Fixture Removal (AFR) algorithms

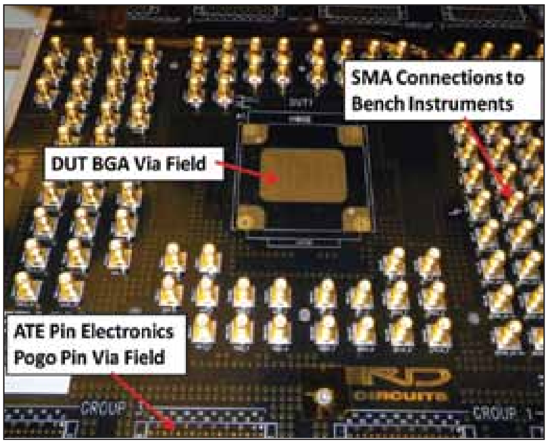


Figure 1 • Example PCB with BGA via field for signal path characterization.

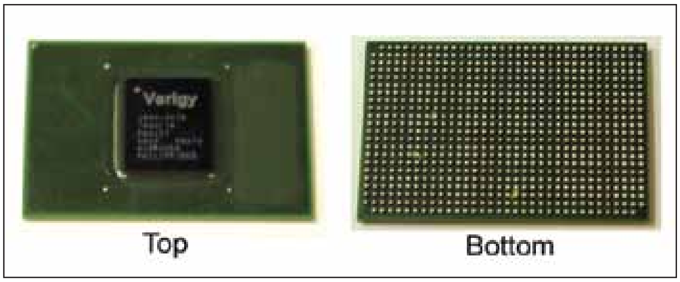


Figure 2 • BGA style DUT with a 1 mm pitch.

can simplify calibrations even further by eliminating the need for a full TRL calibration [3]. Results of this process will be demonstrated by acquiring measurements of crosstalk in the PCB BGA via field on an Automated Test Equipment (ATE) DUT Board for a 1 mm pitch BGA device.

Multi-port Fixture Design

Measurement accuracy is directly related to how well the connecting electrical fixture can be removed from the measurement. Simple DC loss calibrations no longer work at high frequencies where reflections, crosstalk, and frequency dependent absorption can significantly degrade the desired signal. Advanced calibration techniques can in theory remove all of these effects, but calibration tolerances and measurement sensitivity cannot be ignored and a first step to improving calibration accuracies for fixture removal is to minimize the signal degradation caused by the fixture. In the case of a 744 pin BGA device with a 1 mm pitch shown in Figure 2, one finds that the impedance of a signal pin varies depending upon the surrounding return path topology. If one wants to characterize a signal path of the connecting PCB footprint or BGA socket connection, then it is necessary to also provide full connection of all of the surrounding return paths.

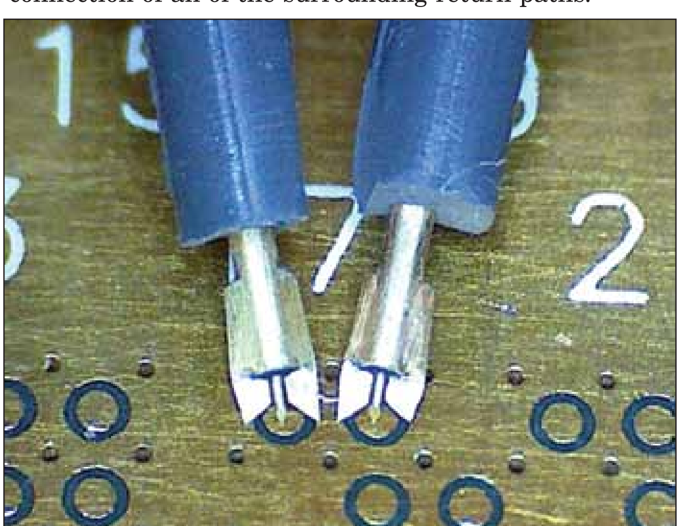
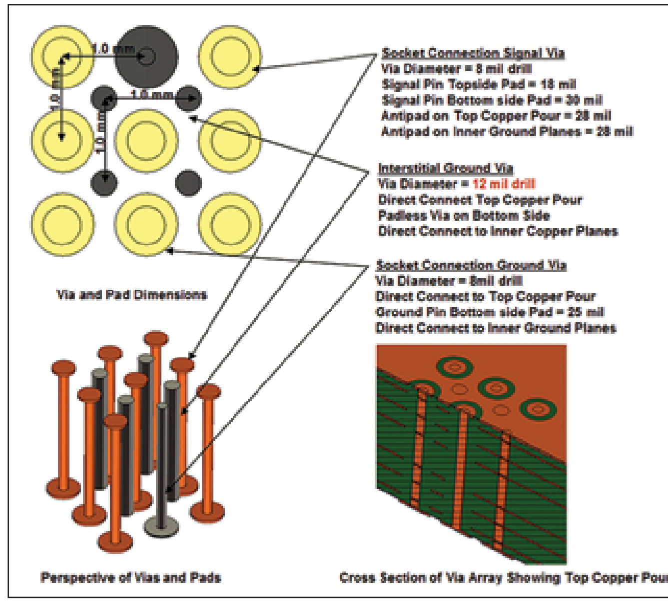


Figure 3 • Micro-Coaxial Ground-Signal-Ground probes.



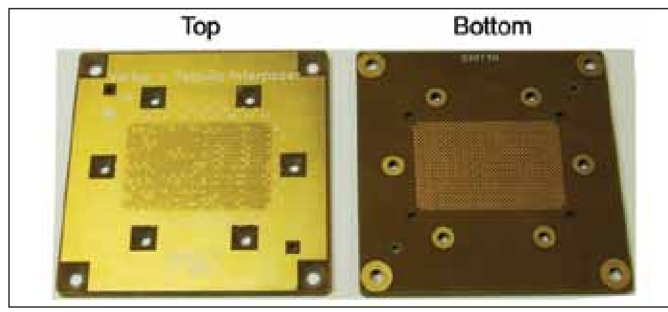


Figure 4 • Multi-layer controlled impedance PCB interposer.

One method of achieving this is to design a small multi-layer interposer to provide a low crosstalk, controlled impedance connection to the coaxial cabling of the measurement system [4]. The PCB interposer simply brings all of the BGA footprint connections up to a top surface PCB layer where all BGA grounds are connected to a single ground fill that surrounds the signal via pads. This provides an excellent 360 degree access for connecting with a low crosstalk Ground-Signal-Ground micro-coaxial probe tip as shown in Figure 3. The figure also shows the addition of four surrounding ground vias added around every signal via pad in the PCB interposer to reduce crosstalk and improve the controlled impedance of the electrical fixture.

The design of the ground via drill sizes are limited to a minimum PCB fabrication size to maximize the distance from the large bottom side pads required for contacting to the PCB footprint or socket pogo pins. Impedance control is done by adjusting the signal via diameter and internal ground layer anti-pads to optimize for 50 Ohm across the entire structure as shown in Figure 4. Bottom side pads are mechanically removed on the ground vias to avoid shorting to the larger signal pads that connect to the PCB footprint or BGA socket pins.

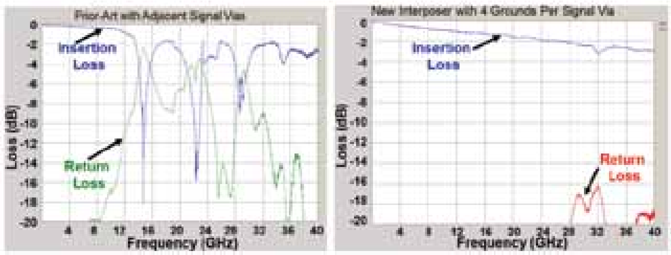


Figure 5 • Probe Interposer performance without additional impedance controlling ground vias on the left and with them on the right.

The measured performance of the Probe Interposer combination for the electrical fixture shows excellent signal transmission to the full bandwidth of the 40 GHz measurement. If the interposer is designed without the four additional ground vias around a signal via then the performance is significantly degraded by impedance mismatches and crosstalk that reduce the useable bandwidth to below 15 GHz, as shown in Figure 5.

TRL Calibration with Adapter Removal

The vertical fixture connection to the BGA PCB footprint or BGA socket makes it difficult for creating and measuring calibration standards. To simplify the complexity of the calibration, the TRL structures are constructed using a high performance edge launch 2.4 mm coaxial connector transitioning to a PCB microstrip transmission line to make the connection to the bottom of the probe interposer. This avoids two sided probing, and allows repeatable characterization of multiple probes from one 2-port TRL calibration.

The combination of a TRL calibration with that of Adapter Removal allows one to select a different reference plane location for each of the two Ports on a Vector Network Analyzer (VNA) measurement system [5,6,7]. The adapter provides the connection between the Port 1 reference plane location and the Port 2 reference plane location. In the case of the Probe Interposer, this allows the reference plane to be placed at the TRL reference plane at the bottom of the interposer on Port 1, and at the coaxial connection to the Probe on Port 2. After calibration to these two extended VNA reference planes, the resulting S-Parameter measurement is the electrical performance of just the Probe Interposer fixture. Utilizing this single calibration, multiple probes can each be inserted and characterized for use with the Probe Interposer connection.

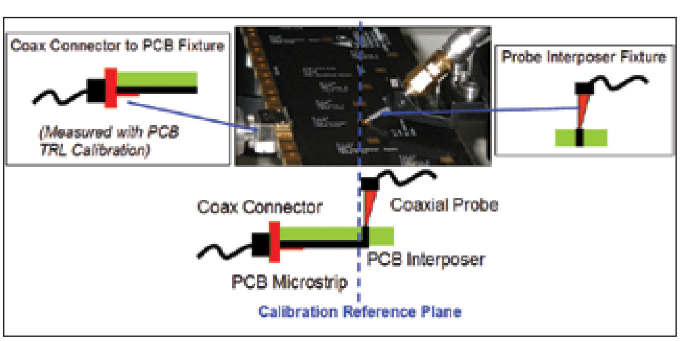


Figure 6 • TRL calibration standards for the probe interposer with asymmetrical connections.

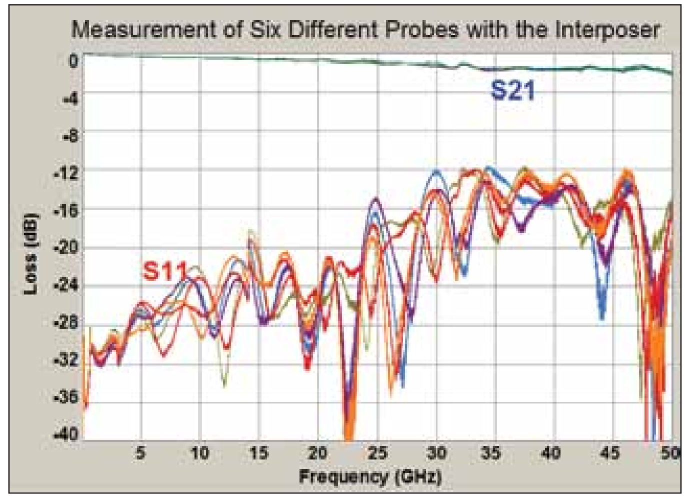


Figure 7 • TRL calibration with adapter removal enables direct measurement of the Probe Interposer fixturing for six different coaxial probes.

Micro-Coaxial probe tips can easily get damaged or modified during usage and recalibration or replacement is not uncommon. If the coaxial 2.4 mm to PCB TRL reference plane adapter is characterized, then one can simply perform a highly repeatable NIST traceable VNA coaxial calibration to the ends of the network analyzer cables, and then use de-embedding of the coax adapter to the bottom of the Probe Interposer to obtain the Probe Interposer S-Parameters.

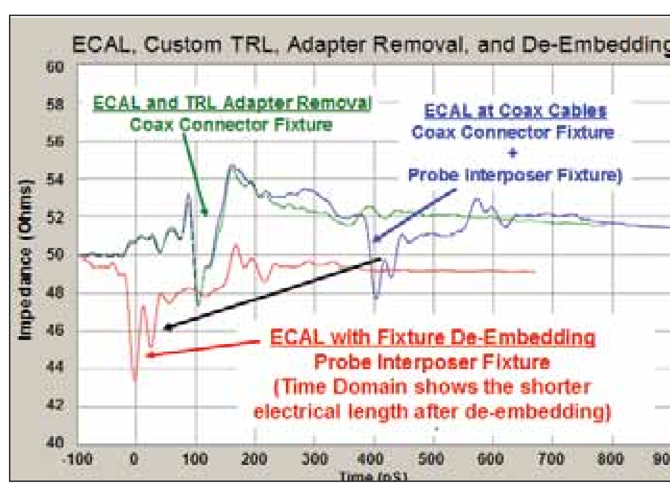


Figure 8 •Time Domain plots of the S11 reflection data show how the Probe Interposer S-Parameters can be obtained by de-embedding the coaxial 2.4 mm to PCB adapter from an automated VNA E-CAL calibration to the ends of the coaxial cables.

This is best illustrated by looking in the time domain to see the full path of discontinuities when measured with a VNA NIST traceable automated electronic E-CAL calibration. Figure 8 shows this full path in blue with both the coaxial 2.4 mm adapter and the Probe Interposer impedance variations. The coaxial 2.4 mm to PCB adapter portion is characterized by selecting the coax 2.4mm reference plane for Port 1 and the bottom of the Probe Interposer TRL reference plane for Port 2. The coaxial 2.4mm to PCB adapter going to the Probe Interposer is then defined as the adapter going from Port 1 to Port 2 in the VNA TRL with Adapter Removal calibration.

The resulting measurement in green in Figure 8 shows just the impedance and electrical length of the coaxial 2.4 mm connector to PCB fixturing. This is then de-embedded from the full path measurement in blue to end up with just the electrical performance of the Probe Interposer shown in red. Making use of automated electronic coaxial calibrations and batched file de-embedding of the fixture significantly reduces connector repeatability and human errors that are always a challenge with high port count calibrations and measurements.

Symmetrical 2x Through Calibration (AFR)

The previous section showed how TRL calibration standards can provide a method of calibrating to a reference plane that is vertically located relative to the planar PCB surface. The use of the horizontal microstrip connection to the bottom of the Probe Interposer does simplify the creation of the multiple line lengths for the TRL calibration standards, but does not exactly replicate the vertical connection that the Probe Interposer makes to the PCB BGA interface or BGA socket. An alternative method is to make use of calibration techniques that only require a single symmetrical through path where half of the path is the desired electrical fixture and the length is 2 times the fixture length x, hence the name “2x Through” calibration standard [3].

The 2x Through path is simply created by connecting two symmetrical Probe Interposers together as shown in Figure 9. The electrical connection between the two contacting surfaces can be improved with a thin vertical interconnect material such as Paricon’s Pariposer material [8]. If a BGA socket is used between the two Probe Interposers then the reference plane can be placed in the middle of the socket. This alternative method does require two sided probing and the need for mirror image PCB interposers to enable back to back connection of the signal and ground BGA ball-out connections.

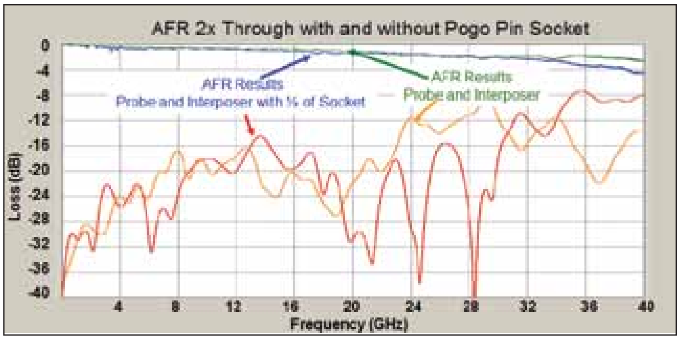


Figure 10 • Alternative AFR calibration using a 2x through path to measure the Probe Interposer.

Implementing a second calibration technique also provides another level of confidence and understanding of how sensitive the reference plane is for a particular measurement location. The measurements for the back-to-back probe interposer with and without the BGA socket were done with an automated E-Cal calibration to the ends of the VNA coaxial cables, and then Agilent’s PLTS software provides the Automatic Fixture Removal (AFR) algorithm for splitting the measurement of the 2x through standard into two parts for de-embedding of the fixture from the VNA measurement.

The AFR 2x through measurement results in Figure 10 reconfirm the wide bandwidth performance of the Probe Interposer that were measured with the TRL standards. Using this technique one can also include the BGA socket and place the reference plane in the middle of the pogo pins in the vertical direction. The resulting data shown in blue in Figure 10 demonstrates that the Probe Interposer to BGA socket transition has little degradation on the bandwidth and that the Probe Interposer design provides a robust connection to the BGA socket.

Multi-port Crosstalk Measurements with Fixture Removal

Now, with the Probe Interposer design verified and multiple probe interposer fixtures characterized it is time

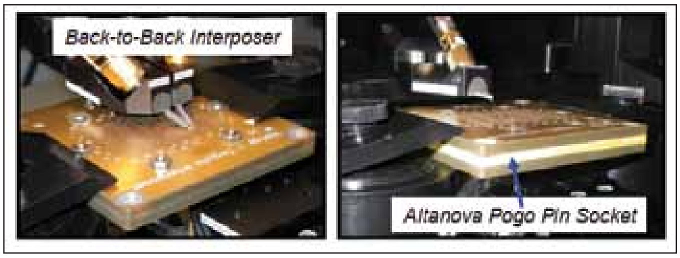


Figure 9 • Two sided probing measurement of the 2x through path with back to back Probe Interposers on the left, and with the BGA socket added on the right.

Figure 11 • 12-Port VNA measurement of 6 ATE DUT Board signal paths with 6 adjacent Probe Interposer connections fanning out to 6 SMA connections.

for measuring the desired ATE DUT Board signal path [8]. At one end is the BGA footprint with the BGA socket and at the other is an SMA connection. The measurement of the signal path as well as crosstalk to adjacent signal paths was done using a 12-Port VNA measurement with six of the Probe Interposer fixture connections going to six SMA connectors as shown in Figure 11. The additional VNA connections not only provide crosstalk data, but also prevent resonances that can occur when signals couple to adjacent signal paths that are left un-terminated.

Calibration of the VNA is done using the automated E-CAL NIST traceable VNA standards for all 12-ports with a reciprocal through (unknown through) to minimize cable movement phase errors. The resulting measurements can then be batch processed to remove the Probe Interposer electrical effects from the desired VNA Port connections to obtain the final ATE DUT Board signal path insertion loss and return loss performance as shown in Figure 12.

In this example of the ATE DUT Board for a 1 mm pitch device it was also possible to measure the signal path with and without the BGA socket to evaluate the electrical degradation that is contributed by the transition of the socket interfacing to the PCB BGA footprint. Figure 12 shows this data for both frequency and time domain highlighting the fact that PCB losses dominate the S21 insertion loss and only a small amount of ripple is added when the socket is included in the signal path.

The multi-port measurement also enables one to look at the crosstalk between adjacent signal paths. Again the measurements are done with and without the BGA socket to help quantify the amount of crosstalk that is contributed by the socket, versus that of the PCB BGA via field. The near end crosstalk has the expected higher magnitude with no significant dielectric losses in the path, and the far end crosstalk with significant signal path attenuation is less of a problem in this ATE application. The socket does contribute to the crosstalk, but the majority of the crosstalk comes from the BGA footprint via field with the transition to stripline routing.

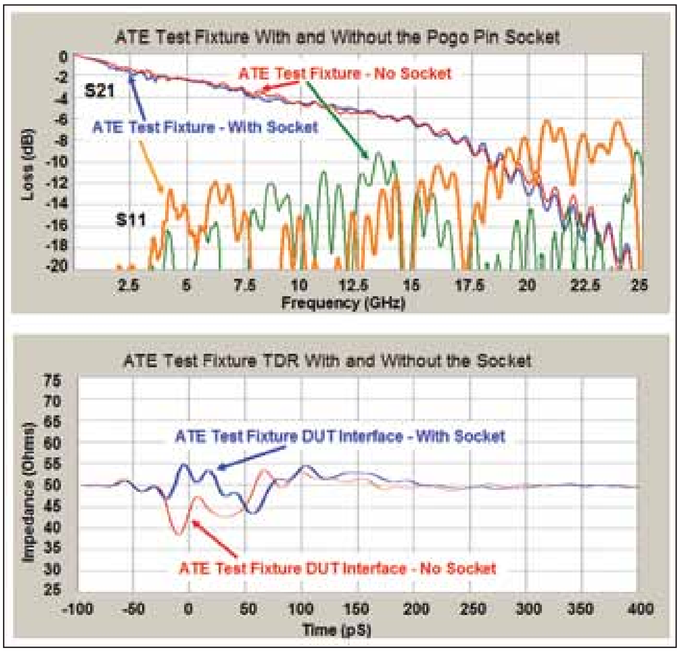


Figure 12 • ATE DUT Board signal path with and without the BGA socket. Top graph is loss vs. frequency and the bottom graph shows the impedance variations at the socket to PCB interface.

Summary

Full characterization of multi-port signal paths on modern PCBs can be quite challenging for high speed digital BGA devices. The design of a Probe Interposer fixture with low crosstalk G-S-G coaxial probes and a multi-layer PCB interposer with added ground vias per signal via shows the feasibility of probing a BGA PCB footprint to frequencies extending past 40GHz.

The removal of the electrical effects of the Probe Interposer electrical fixture that connects to the measuring VNA instrumented was demonstrated using a combination of traditional TRL standards along with Adapter Removal and de-embedding. This calibration method enables characterization of multiple Probe Interposer electrical fixtures and greatly simplifies replacement of damaged probes during a measurement or re-calibration after usage. The alternative AFR two sided calibration with a simple 2x through path calibration standard provided additional options for the placement of the reference plane, such as in the middle of the BGA socket pins. Implementing two different calibration methods also helps to verify the quality of the calibration at the selected reference plane.

Full-path S-Parameter measurements of an ATE DUT Board for a 1 mm pitch BGA device were successfully demonstrated using the Probe Interposer fixture for connecting to the VNA instrument. The ability to calibrate out the Probe Interposer effects from the measurement

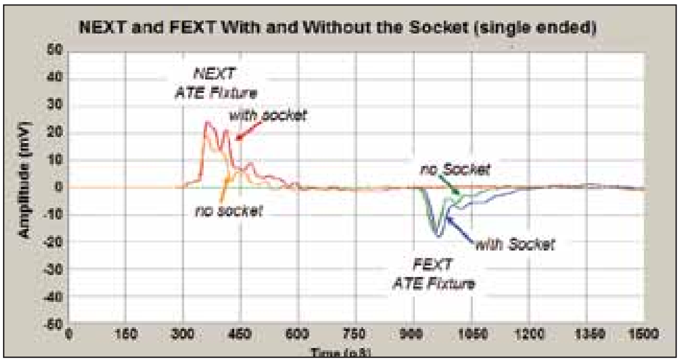


Figure 13 • ATE DUT Board NEXT and FEXT crosstalk between adjacent BGA connections with and without the BGA socket in the signal path.

provides accurate path loss and impedance profiles for incorporating into system simulations and modeling.

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