S-Parameter Measurements
Basics for High Speed Digital Engineers

Frequency dependent effects are becoming more prominent with the increasing data rates of digital systems. Differential circuit topology is commonly-used as an implementation method, with the goal of enhancing the data carrying capable of the physical layer. Simple impedance and delay measurements of copper transmission lines are not sufficient to ensure accurate analysis of gigabit interconnects. The challenge to push design rules to the limit, now requires the use of concurrent time and frequency domain measurements.

The vector network analyzer (VNA) has traditionally been used by microwave engineers to design antennas and test microwave components. Today, a whole new generation of digital design engineers have learned to use the VNA to gain valuable insight into the performance of high speed digital interconnect such as backplanes, printed circuit boards, cables, connectors and even IC packages. These interconnect devices under test are linear and passive, so linear superposition holds, and differential S-parameters can be measured easily and accurately. Furthermore, the superior dynamic range of the VNA enables much higher precision when characterizing low level signals such as crosstalk. Importantly, the advanced error correction capabilities of the VNA can move the reference plane closer to the device under test and remove the effects of lossy test fixtures. This results in better designed channels that transmit much higher data rates with very few errors at the receiver.

This white paper will create a strong foundation of test and measurement science related to s-parameter measurements and analysis. Signal integrity engineers who are just beginning their journey into high speed design will undoubtedly learn new concepts that can enable them to be more successful in the lab making measurements and, in the office, doing analysis. More experienced signal integrity engineers will recognize many of the concepts and most likely pick up a few more clever tips and tools to make life easier during their workday.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why Use S-Parameters?</td>
<td>3</td>
</tr>
<tr>
<td>Digital signal Transitions in Channels</td>
<td>4</td>
</tr>
<tr>
<td>Digital signals vs. Analog signals</td>
<td>5</td>
</tr>
<tr>
<td>Transfer function of sine waves – What is the output?</td>
<td>6</td>
</tr>
<tr>
<td>What are S-parameters?</td>
<td>7</td>
</tr>
<tr>
<td>What are S-parameters? - Expressions</td>
<td>8</td>
</tr>
<tr>
<td>What are S-parameters? Lightwave Analogy</td>
<td>9</td>
</tr>
<tr>
<td>Mode conversion on a differential pair</td>
<td>10</td>
</tr>
<tr>
<td>Balanced devices</td>
<td>11</td>
</tr>
<tr>
<td>4-port Differential S-parameters</td>
<td>12</td>
</tr>
<tr>
<td>S-parameter measurements basics – Vector Network Analyzer (VNA)</td>
<td>13</td>
</tr>
<tr>
<td>Frequency domain → Time domain</td>
<td>14</td>
</tr>
<tr>
<td>S-parameter &amp; TDR/TDT measurements</td>
<td>15</td>
</tr>
<tr>
<td>Time domain → Frequency domain</td>
<td>16</td>
</tr>
<tr>
<td>TDR (Sampling) scopes</td>
<td>17</td>
</tr>
<tr>
<td>VNA vs. TDR Scopes – Advantage of VNA</td>
<td>18</td>
</tr>
<tr>
<td>Importance of calibration – With or without the cal.</td>
<td>19</td>
</tr>
<tr>
<td>Importance of calibration – Error types</td>
<td>20</td>
</tr>
<tr>
<td>Importance of calibration – Systematic error</td>
<td>21</td>
</tr>
<tr>
<td>Importance of calibration – Calibration kits</td>
<td>22</td>
</tr>
<tr>
<td>How do we use S-parameters? – On scopes</td>
<td>23</td>
</tr>
<tr>
<td>How do we use S-parameters? – With simulation SW</td>
<td>24</td>
</tr>
<tr>
<td>Why use S-parameters?</td>
<td>25</td>
</tr>
<tr>
<td>Summary</td>
<td>26</td>
</tr>
<tr>
<td>Keysight High-Speed Digital &amp; Signal Integrity Solutions</td>
<td>27</td>
</tr>
<tr>
<td>Who Uses Time Domain Reflectometry?</td>
<td>28</td>
</tr>
<tr>
<td>What is PNA/ENA Option TDR?</td>
<td>28</td>
</tr>
<tr>
<td>ENA Option TDR Compliance Test Solution</td>
<td>29</td>
</tr>
<tr>
<td>Additional Resources</td>
<td>35</td>
</tr>
</tbody>
</table>
Why Use S-Parameters?

This is a sample of a typical transmitter device consisting of a chip, a package, and a card. A channel (transmission lines/traces) must match the characteristic impedance for a controlled impedance environment within the channel (50Ω as shown in the top-right figure). However, the output signal/waveform at the output connector (bottom-right eye diagram) is degraded/distorted compared to the input signal/waveform (top-left eye diagram). Why is the waveform at the connector output degraded? Is it not enough measuring the characteristic impedance?

Transmission line matches the characteristics impedance (50Ω).
- Why is the waveform @ Connector output degraded?
- Is it not enough measuring the characteristic impedance?
Digital signal Transitions in Channels

Fast edges of digital signal transitions from logic level zero to logic level one become degraded into slow edges as they transmit through the copper channel.

Comparing waveforms before and after transmitting the channel for 1Gbps and 10Gbps, the 10Gbps waveform is dramatically distorted. It’s far from an ideal digital signal. The higher the bitrate, the more we need to observe/manage the digital signal same as an analog signal.
Digital signals vs. Analog signals

100MHz square wave

Let’s see 100MHz square wave for instance. With digital interpretation, it’s a 10101… 200Mbps bit pattern.

On the other hand, with analog interpretation, it’s a composite(synthesized) waveform consisting of sine waves, 100MHz fundamental and harmonics.

Digital interpretation

200Mbps 10101….. bit pattern

Analog interpretation

100MHz square wave which consists of sine waves

Digital Signals = Analog Signals (consists of sine waves)
Transfer function of sine waves – What is the output?

Devices that behave linearly only impose magnitude and phase changes on input signals. Any sinusoid appearing at the input will also appear at the output at the same frequency. No new signals are created.

This is an example of a sine wave applied to a linear device which has the Output/Input and Phase characteristics shown below. The device imposes a non-uniform amplitude and phase change to each frequency component. At the frequency point 1, we can see the output signal same as the input signal (dotted line in the bottom-left figure). At 2, amplitude is decreased as half and phase is delayed as -90 degree (solid line in the bottom-left figure). At 3, no signal can be detected from output.

When a single sinusoid is passed through a linear network, amplitude and phase changes are not to be considered as distortion. However, when a complex time-varying signal is passed through a linear network, the amplitude and phase shifts can dramatically distort the time-domain waveform. Therefore both amplitude and phase information in frequency domain are important. Then, S-parameters are the parameter which supports both information and has many advantages for high frequency device characterization.

### S-parameters

- **Amplitude variation** → **Insertion loss**
- **Timing variation** → **Phase shift**

**Signal amplitude/phase are changed depending on frequency:**

*Information on amplitude and/or phase characteristics in frequency domain → S-parameters*
What are S-parameters?

S-parameters are complex matrix that show Reflection/Transmission characteristics (Amplitude/Phase) in frequency domain. This type of test equipment is called “Stimulus/Response” and applies to both Vector Network Analyzers (VNA) and Time Domain Reflectometers (TDR).

A two-port device has four S-parameters. The numbering convention for S-parameters is that the first number following the “S” is the port where the signal emerges, and the second number is the port where the signal is applied. So S21 is a measure of the signal coming out port 2 relative to the RF stimulus entering port 1. When the numbers are the same (e.g., S11), it indicates a reflection measurement, as the input and output ports are the same.

Reflection/Input $= \text{Reflection coefficient} \rightarrow S_{11}, S_{22}$

Transmission/Input $= \text{Transmission coefficient} \rightarrow S_{21}, S_{12}$

**S-parameters are complex matrix that show Reflection/Transmission characteristics (Amplitude/Phase) in frequency domain.**
What are S-parameters? - Expressions

With amplitude and phase information, we can quantify the reflection and transmission characteristics of devices. Some of the common measured terms are scalar in nature (the phase part is ignored or not measured), while others are vector (both magnitude and phase are measured). For example, return loss is a scalar measurement of reflection, while impedance results from a vector reflection measurement. Some, like group delay, are purely phase-related measurements.

Reflection, $S_{11}/S_{22}$: Reflections (Return loss), Impedance, Admittance, VSWR. Smith chart is one of display methods for complex reflection coefficient.

Transmission, $S_{21}/S_{12}$: Gain/Loss (Insertion loss), Phase, Group delay (Delay time).
Differential signaling

In today’s high-speed digital applications, differential signaling (differential circuit topology) is widely and commonly used. Let’s review pros and cons of differential signaling.

**A method of transmitting information electrically with two complementary signals sent on a differential pair.**

**Pros**

1. High noise immunity: Common-mode rejection
2. High margin for signal attenuation: Receiver takes double voltage
3. Low voltage operation: Low power consumption, low di/dt (EMI suppression)
4. EMI reduction: Cancel out a magnetic field (complementary current)

**Cons:**

1. Large footprint: double traces, more area needed
Mode conversion on a differential pair

However, non-ideal differential transmission lines do not exhibit benefits (pros) described in the previous slide. A differential transmission line with even a small amount of asymmetry, will produce a common signal that propagates through the device. This asymmetry can be caused by any physical feature that is on one line of the differential pair and not the other line, including solder pads, jags, bends and digs. This mode conversion is a source of EM interference (emission/radiation). Most new product development must pass the EMC compliance testing near the end of the design cycle. Very often the test results show that the design exhibits EM interference or susceptibility (immunity). However, there is usually very little insight as to what physical characteristic is causing the problem. Mode conversion analysis provides the designer with that insight so that EM problems can be resolved early in the design stage.

**Unexpected mode conversion will be occurred on a non-ideal differential device. Non-ideal means anything on one line of the differential pair not on the other line (asymmetry).**
Balanced devices

Standard Single-ended devices generally have one input port and one output port. Signals on the input and output ports are referenced to ground. On the other hand, balanced devices have two pins on either the input, the output, or both. The signal of interest is the difference and average of the two input or output lines, not referenced to ground.

Differential mode responses can be obtained by balanced measurements and are represented by Differential S-parameters. The format of the parameter notation “Sxyab”, where “S” stands for S-parameter, “x” is the response mode (differential or common), “y” is the stimulus mode (differential or common), “a” is the response port number and “b” is the stimulus port number. This is typical nomenclature for frequency domain S-parameters.

**Differential mode responses are represented by Differential S-parameters**
4-port Differential S-parameters

The sixteen S-parameters that are obtained by fully characterizing a differential interconnect can be categorized into 4 stimulus/response quadrants.

In order to interpret the large amount of data in the differential parameter matrix, it is helpful to analyze one quadrant at a time. The first quadrant is defined as the upper left 4 parameters describing the differential stimulus and differential response characteristics of the device under test. This is the actual mode of operation for most high-speed differential interconnects, so it is typically the most useful quadrant that is analyzed first. It includes input differential return loss (Sdd11), input differential insertion loss (Sdd21), output differential return loss (Sdd22) and output differential insertion loss (Sdd12).

The second and third quadrants are the upper right and lower left 4 parameters, respectively. These are also referred to as the Differential quadrants. This is because they fully characterize any mode conversion occurring in the device under test, whether it is common-to-differential conversion (EMI susceptibility, immunity) or differential-to-common conversion (EMI interference, emission/radiation). Understanding the magnitude and location of mode conversion is very helpful when trying to optimize the design of interconnects for gigabit data throughput.

The fourth quadrant is the lower right 4 parameters and describes the performance characteristics of the common signal propagating through the device under test. If the device is designed properly, there should be minimal mode conversion and the fourth quadrant data is of little concern. However, if any mode conversion is present due to design flaws, then the fourth quadrant will describe how this common signal behaves.
S-parameter measurements basics – Vector Network Analyzer (VNA)

For two-port VNA (e.g., Keysight E5071C ENA Series Network Analyzer or N5225B PNA Series Network Analyzer)

S11 (=A/R1) and S21 (=B/R1) are determined by measuring the magnitude and phase of the incident (R1), reflected (A) and transmitted (B) voltage signals when the output is terminated in a perfect Zo (a load that equals the characteristic impedance of the test system). This condition guarantees that R2 is zero, since there is no reflection from an ideal load. S11 is equivalent to the input complex reflection coefficient or impedance of the DUT, and S21 is the forward complex transmission coefficient. Likewise, by placing the source at port 2 and terminating port 1 in a perfect load (making R1 zero), S22 (=B/R2) and S12 (=A/R2) measurements can be made. S22 is equivalent to the output complex reflection coefficient or output impedance of the DUT, and S12 is the reverse complex transmission coefficient.

Note that 4-port VNA is required for fully characterizing a 2-port differential device.

Block diagram (2-port VNA)

Note: Balanced measurements require 4-port VNA

**Measure amplitude & phase of components by using sine wave frequency sweep**
Frequency domain → Time domain

S-parameters (frequency response) can be transformed into the time domain parameters (impulse response → step response) by performing an inverse Fast Fourier transform (IFFT).

The matrix representing the time domain will have similar notation, except the “S” is replaced by a “T” (i.e. Tdd11).

Using Inverse Fast Fourier Transform techniques, the frequency domain response can be mathematically transformed into the time domain response.
S-parameter & TDR/TDT measurements

Both, time and frequency domain data help us understand device characteristics. Just four differential parameters are shown in this slide, but other parameters such as mode conversions are often required to evaluate a device thoroughly.

Both time and frequency domains analysis are valid and feasible
Time domain $\rightarrow$ Frequency domain

It's also possible that the time domain parameters (step response $\rightarrow$ impulse response) can be transformed into S-parameters (frequency response) by performing a fourier transform (FT).

Which is the best solution?
TDR (Sampling) scopes

Let's review the measurement principle of TDR scopes. The TDR instrument accomplishes this task with a fast step (step generator) with little overshoot in concert with a wideband receiver (sampler) to measure step response.

Input step signal and derive impedance/loss from reflection/transmission measurements
VNA vs. TDR Scopes – Advantage of VNA

The VNA uses a precise sine wave and sweeps frequency as a narrow band receiver tracks the swept input response. This narrow band receiver achieves low noise and high dynamic range of the VNA. Whether the data acquisition hardware is time domain based or frequency domain based, Differential data is also compiled in a 4-port measurement system. In this regard, however, VNA offers more accurate measurements with state of the art calibration techniques. Furthermore, the VNA offers faster measurement speeds thanks to a high dynamic range, and higher robustness against ESD with protection circuits implemented inside the instrument for all ports while maintaining excellent RF performance.

- Low Noise
- High dynamic range
- Fast measurement speed
- State of the art calibrations
- ESD Robustness
- Support both time and frequency domain measurements with various format

VNA offers more accurate measurements
Importance of calibration – With or without the cal.

Considerable difference with or without the cal → Calibration method is very important
Importance of calibration – Error types

There are three basic sources of measurement error: systematic, random and drift.

Systematic errors are due to imperfections in the analyzer and test setup. They are repeatable (and therefore predictable) and are assumed to be time invariant. Systematic errors are characterized during the calibration process and mathematically removed during measurements.

Random errors are unpredictable since they vary with time in a random fashion. Therefore, they cannot be removed by calibration. The main contributors to random error are instrument noise (source phase noise, sampler noise, IF noise).

Drift error are due to the instrument or test-system performance changing after a calibration has been done. Drift is primarily caused by temperature variation and it can be removed by further calibration(s). The timeframe over which a calibration remains accurate is dependent on the rate of drift that the test system undergoes in the user's test environment. Providing a stable ambient temperature usually goes a long way towards minimizing drift.

Systematic error

- Due to imperfections in the analyzer and the test setup
- Assumed to be time invariant (predictable)
- It is possible to eliminate them mathematically at the time of measurement by determining the characteristics of these errors through calibration

Random error

- Vary with time in random fashion (unpredictable)
- Main contributors:
  - Instrument noise (Signal source phase noise, IF noise, etc...)
  - Switch and connector repeatability
- Cannot be removed by calibration

Drift error

- Due to system performance changing after a calibration has been done
- Primarily caused by temperature variation
Importance of calibration – Systematic error

There are major systematic errors associated with network measurements. These errors relating to signal leakage are directivity and crosstalk. Errors related to signal reflections are source and load match. The final class of errors are related to frequency response of the receivers and are called reflection and transmission tracking. The full two-port error model includes all six of these terms for the forward direction and the same six (with different data) in the reverse direction, for a total of twelve error terms. This is why we often refer to two-port calibration as twelve-term error correction.

**Six forward and six reverse error terms yields 12 error terms for two port devices**
Importance of calibration – Calibration kits

Vector-error correction is the process of characterizing systematic error terms by measuring known calibration standards, and then removing the effects of these errors from subsequent measurement.

Traditional two-port calibration usually requires twelve measurements on four known standards (short-open-load-through or SOLT). Some standards are measured multiple times (e.g., the through standard is usually measured four times). The standards themselves are defined in a cal-kit definition file, which is stored in the network analyzer.

Electronic calibration (ECal) replaces the traditional calibration technique, which uses mechanical standards. Mechanical standards require numerous connections to the test ports for a single calibration. These traditional calibrations require intensive operator interaction, which is prone to error. With ECal, a full one to four port calibration can be accomplished with a single connection to the ECal module and minimal operator interaction. This results in faster and more repeatable calibrations.

By reducing the number of connections required for a calibration, it can: Calibrate faster, save time and make measurement sooner / Reduce the chance of operator error, for greater confidence in the calibration / Reduce the wear on connectors, for lower repair cost on both the test port connectors and calibration standards.

E-Cal offers fast, easy, and accurate calibration
How do we use S-parameters? – On scopes

Sometimes it’s difficult to probe a transmitter output on a die, but it’s possible to move the observation point (simulate a waveform at the target point) from the actual probing point with S-parameters on an oscilloscope (Keysight InfiniiSim Transformation Toolset). [https://www.keysight.com/find/infiniiSim](https://www.keysight.com/find/infiniiSim)

*It’s easy to move the observation point with S-parameters on a signal analysis software*
How do we use S-parameters? – With simulation SW

S-parameters are easily imported and used for circuit simulations in electronic-design automation (EDA) tools like Keysight’s Advanced Design System (ADS). S-parameters are the shared language between simulation and measurement.

How good is the transmission line?

Physical Layer Test System (PLTS) signal integrity specialist software with PXI-VNA digital interconnect test system hardware (www.keysight.com/find/plts).
Why use S-parameters?

Bandwidth is limited by transmission line (insertion loss = -15 dB @10GHz) → S-parameter measurements are critical in high speed digital applications.

Bandwidth is limited by passive interconnect transmission line

- S-parameter measurements are ultimate in accuracy
- S-parameters with PLTS allow multi-domain analysis
- S-parameters from VNAs have highest dynamic range (Xtalk)
Summary

S-parameter measurements are required in today’s high-speed digital industry due to Hyperscale Data Network gigabit channels

- S-parameters are complex matrix that show Reflection/Transmission characteristics (Amplitude/Phase) in frequency domain.
- S-parameters support various formats (Rectangular, Smith chart, Polar, …)
- Differential signal may cause mode conversion (e.g., EM emission)
- Differential S-parameters cover such mode conversions
- S-parameters can be transformed into TDR/TDT
- VNA vs. TDR: VNA offers more accurate measurements
- With S-parameters, it’s easy to move the observation point on scopes, and to simulate waveform under various conditions on simulation software.
- Using S-parameters with signal integrity specialist software such a Physical Layer Test System (PLTS) enables critical multi-domain analysis to observe frequency domain, time domain, eye diagram domain, multi-channel simulation and crosstalk.
Keysight High-Speed Digital & Signal Integrity Solutions

Keysight offers high speed digital and signal integrity solutions from design and simulation to compliance test.

Offer whole engineering support (customized, flexible) from installation to implementation.
Who Uses Time Domain Reflectometry?

Time Domain Reflectometry (TDR) is used primarily by digital design engineers who want to characterize passive interconnects such as printed circuit boards, backplanes, cables, connectors and test fixtures. The figure of merit is typically ohms per unit length and this can give extremely useful information to the designer. Developing a controlled impedance environment for high speed digital signals is the best way to guarantee pristine data transmission channel with no bit errors at the receiver. This TDR tool will avoid problems such as crosstalk, impedance mismatch, reflections, amplitude degradation and skew.

What is PNA/ENA Option TDR?

The ENA Option TDR is an application software which provides a one-box solution: We can measure both time domain and frequency domain measurements, and additionally eye diagram analysis on this product. It offers three breakthroughs, advantages against competitive solutions: Simple and Intuitive Operation / Fast and Accurate Measurements / ESD Robustness.

The ENA Option TDR is an application software embedded on the ENA, which provides a one-box solution for high speed serial interconnect analysis.

3 Breakthroughs
For Signal Integrity Design and Verification

Simple and Intuitive Operation

Fast and Accurate Measurements

ESD Robustness
ENA Option TDR Compliance Test Solution

Certified MOIs

ENA Option TDR is certified for a variety of high-speed serial standards.

For cable/connector compliance testing, certification is available for USB3, HDMI, SATA, DisplayPort, 100BASE-TX, 10GBASE-T Ethernet, MHL and PCI Express.

For transmitter/receiver Hot TDR testing, certification is available for SATA, MIPI (D-PHY, M-PHY) and Thunderbolt.

MOI (or method of implementation) documents, and state files are currently available from the Keysight web site. State files contain pre-configured setups in accordance with the standard requirements and allows for quick and easy measurements.

Compliance test solutions (i.e. Certified MOIs) with the ENA Option TDR are available at: www.Keysight.com/find/ena-tdr_compliance

*For more details about Thunderbolt and BroadR-Reach compliance test solution using the ENA Option TDR, contact Keysight Sales representative
ENA Option TDR Compliance Test Solution Cnt’d

Many of the test centers for high speed serial compliance testing have already adopted ENA Option TDR. When looking for an instrument for pre-compliance testing, it is always preferable to use instrumentation used at the test centers to ensure measurement correlation.

Test Centers Support ENA Option TDR

ENA Option TDR is used world wide by certified test centers of USB, HDMI, DisplayPort, MHL, Thunderbolt and SATA.
ENA Option TDR Compliance Test Solution Cnt’d

Both materials are available in this compliance webpage on [http://www.keysight.com](http://www.keysight.com). As you can see, ENA Option TDR supports a variety of high-speed digital standards. In the next two slides, I’m going to show those contents briefly.

ENA Option TDR Compliance Test Solution Cnt’d

Test solution overview helps you understand what kind of measurements are required. For example, let’s see the HDMI compliance test overview. Start from testing purpose, compliance test setup, measurement parameters, and required equipment with accessories. You can grab the information quickly.

**Test Solution Overview**

Brief guide of test requirements and necessary test resources
ENA Option TDR Compliance Test Solution Cnt’d

MOI, method of implementation shows the detailed measurement procedure. Besides that, state file included in the test package is also available, which contains pre-configured setups in accordance with the standard requirements and allow for quick and easy measurements. Using MOI and state file, you can efficiently perform compliance test.

**MOIs & State Files**

Detailed measurement procedure and useful test package

**Method of Implementation (MOI)**

**Test package (e.g., HDMI cable assembly test package)**

State file, Eye mask, and Equalizer file
The scalar vector network analyzer allows simple and fast calibration using an electronic calibration module resulting in highly precise multiport s-parameter measurements that correlate well with models. Furthermore, the 32-port 53 GHz wide bandwidth interconnect test system allows all near-end and far-end crosstalk terms to be gathered into one s32p Touchstone file. Powerful multidomain analysis is now within reach of the signal integrity engineer. Whether the test system is in a PXI-chassis as on the left or in streamline USB modules in ruggedized packages on the right, the future of signal integrity measurement science is bright as ever. For more technical details, visit the following websites

www.keysight.com/find/plts

www.keysight.com/find/diref

www.keysight.com/find/RessoBook
Additional Resources

**ENA Option TDR Reference Material**

www.keysight.com/find/ena-tdr

- Technical Overview (5990-5237EN)
- Application Notes
  - Correlation between TDR oscilloscope and VNA generated time domain waveform (5990-5238EN)
  - Comparison of Measurement Performance between Vector Network Analyzer and TDR Oscilloscope (5990-5446EN)
  - Effective Hot TDR Measurements of Active Devices Using ENA Option TDR (5990-9676EN)
  - Measurement Uncertainty of VNA Based TDR/TDT Measurement (5990-8406EN)
  - Accuracy Verification of Keysight's ENA Option TDR Time Domain Measurement using a NIST Traceable Standard (5990-5728EN).

Method of Implementation (MOI) for High Speed Digital Standards

www.keysight.com/find/ena-tdr_compliance

Learn more at: www.keysight.com

For more information on Keysight Technologies' products, applications or services, please contact your local Keysight office. The complete list is available at: www.keysight.com/find/contactus