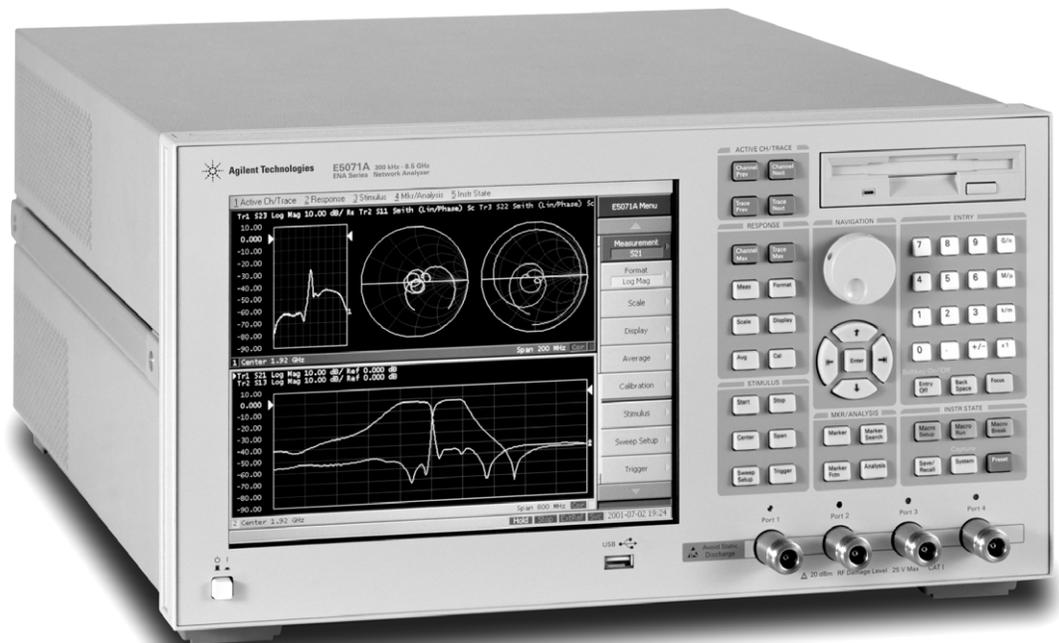# Agilent
Introduction to the
Fixture Simulator Function of the
ENA Series RF Network Analyzers:
Network De-embedding/Embedding
and Balanced Measurement

Product Note E5070/71-1

Agilent Technologies

Introduction

In modern RF circuit evaluation, RF engineers are often required to process the measured S-parameters for various reasons. This is mainly because of the fact that RF network analyzers only allow measurement at well-defined 50 Ω single-ended coaxial interfaces, while current RF components take various forms in order to cope with the ever increasing requirements for smaller size, smaller power consumption, lower price, and so forth. The post measurement data processing is time-consuming work including calculation with an external computer and data transfer between the computer and the analyzer. The fixture simulator is a built-in function of the ENA Series network analyzer, which significantly simplifies and speeds up the post measurement data processing. The fixture simulator contributes to the following four major applications:

- Removal of unwanted test fixture effects
- Component measurement with non-50 Ω port impedance
- Balanced component measurement
- Evaluation of the total network characteristics when external circuits are attached to the component

These four applications are briefly explained below. Firstly, the use of test fixture becomes the norm in RF component measurement as surface mount devices (SMDs) become pervasive, replacing traditional coaxial-interface devices. Growing demand for higher performance RF SMDs requires RF engineers to minimize the unwanted fixture effects in component measurement. A possible solution is to model the fixture and remove its effects mathematically from the measured data. Secondly, there are some RF components that have non-50 Ω port impedance in order to optimize the circuit performance, while the port impedance of a network analyzer is usually 50 Ω. It is possible to convert the port impedance mathematically after the normal 50 Ω measurement. Thirdly, balanced circuits have been employed in RF communication equipment mainly due to its superior performance in noise immunity and EMI radiation. Given the fact that there is no commercialized network analyzer equipped with balanced ports, mathematical conversion from unbalanced to balanced characteristics is a realistic solution to balanced measurement. Finally, some components need to be evaluated based on the performance when they are equipped with external circuits, such as matching circuits. It is useful for these applications if ideal circuits can be mathematically added to the measured data instead of the actual circuit implementation.

The next section of this note provides a bird's-eye view of how the fixture simulator can be used in these applications. Then each application will be discussed in detail as a separate section.

www.agilent.com/find/ena

Overview of
the fixture simulator

The fixture simulator of the ENA Series, as its name suggests, processes the S-parameters obtained in a non-ideal (real) fixture as if the DUT were measured in an ideal fixture. The fixture simulator, with easy to use graphical user interface of the ENA Series, significantly reduces the burden of the post measurement data processing.

Figure 1 shows the functions of the fixture simulator with the physical circuit interpretations of how each function can be used in network measurement. The upper half of the figure describes the single-ended measurement, whereas the lower half describes the balanced measurement. (The port extension and the fixture de-embedding features are commonly used in both types of measurements.) The simulator functions can be used either separately or in combination, according to the applications. For example, it is appropriate to use only the impedance conversion if you evaluate the characteristics of a single-ended 100 Ω component and the fixture effects are negligible. You can use the matching circuit embedding in addition if you need to evaluate the characteristics of the component with a matching circuit.
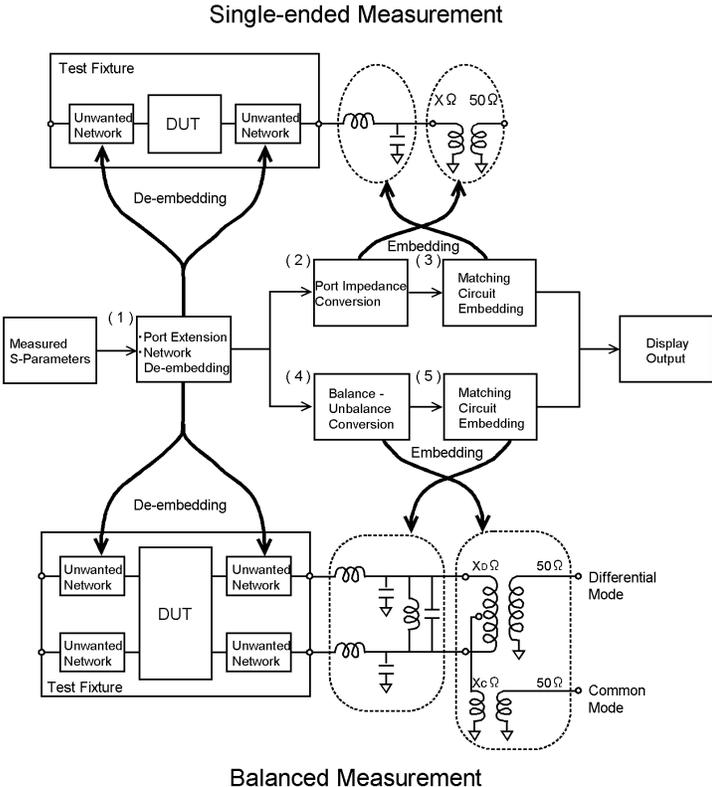
Figure 1. Fixture simulator overview

Overview of the fixture simulator

The following are brief descriptions of the each component (see figure 1).

1. The port extension and the fixture de-embedding can be used to minimize the unwanted effects of the fixture used in the actual measurement.

2. The impedance conversion changes the measurement data as if the component were measured with the analyzer that has the specified port impedance, which is equivalent to embedding the ideal transformer with the appropriate turn ratio.

3. The matching circuit embedding changes the measured data as if the component were equipped with the specified matching circuit.

4. The balance-unbalance conversion transforms the single-ended S-parameters into the mixed mode (differential and common) S-parameters, which can be described as embedding the ideal hybrid balun (balance-unbalance) transformer. Within the conversion, mixed-mode port impedance is also set as specified by the user.

5. The differential matching embedding changes the measurement data as if there were the specified matching circuits connected to the differential ports.

Remove the unwanted test fixture effects: port extension and network de-embedding

When measuring components with non-coaxial interface, such as SMDs, it is inevitable to use a test fixture in order to connect the components to the network analyzer, which has a coaxial interface, as shown in figure 2. As the analyzer is calibrated at the coaxial interface defined as the measurement plane, measured results include the fixture effects between the measurement plane and the device plane. It is essential to carefully design fixtures in order to minimize the fixture effects for accurate measurement. However, fixtures inevitably have physical length and the coaxial to non-coaxial interface transition often induces unwanted effects. Accordingly, accurate characterization of components without coaxial connectors requires the removal of the unwanted fixture effects from the measured results.
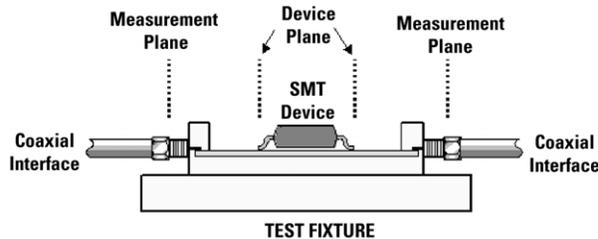

Figure 2. Test fixture configuration

A simple way of removing the fixture effects is to perform a calibration at the ends of the coaxial test cables, and then use port extensions, which extends the measurement planes towards the device plane based on the assumption that the test fixture circuits are perfect transmission lines with the characteristic impedance of 50 Ω. When this assumption is not acceptable, de-embedding of the fixture is a more suitable choice. The fixture simulator performs the network de-embedding calculations according to the fixture S-parameter model specified by the user for each measurement port, which allows the real-time measurement with reduced fixture effects. The fixture models can be transferred to the ENA Series network analyzer as a 2 x 2 S-parameters Touchstone file (.s2p). Figure 3 shows the effect of the fixture de-embedding in the transmission measurement (S_{21}) of the SAW filter: the lower trace includes the unwanted effects of the test fixture, which is removed by the de-embedding in the upper trace. In this example, the fixture is modeled as a loss-less transmission line with a series inductor and a shunt capacitor.
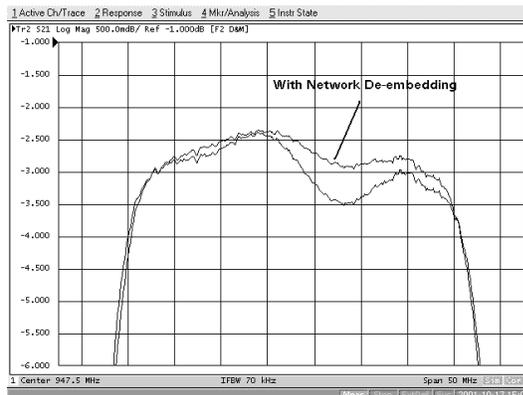
More detailed discussion on S-parameter networks de-embedding, including how to model fixtures, is given in the reference 1, **Agilent application note 1364-1.**

www.agilent.com/find/ena

Figure 3. The effect of the fixture de-embedding in SAW filter measurement

Evaluate non-50 Ω components: port impedance conversion

It is necessary to convert the port characteristic impedance of a network analyzer, when evaluating the components with characteristic impedance other than the analyzer port impedance of 50 Ω. In theory, the port impedance can be converted to any real impedance by using an appropriate transformer. In practice, however, this approach includes several problems: firstly the use of transformers induces measurement errors due to the non-ideal characteristics of the trans- formers, which cannot be removed because of the lack of traceable calibration standards other than 50 Ω. Moreover, RF transformers are relatively narrow band. The more realistic approach of the fixture simulator is that the port impedance is converted by calcula- tions, in accordance with the port impedance specified by the user, which is equivalent to the embedding of ideal transformers in the measurement circuit. (Note that the port impedance is specified with a positive real number in the fixture simulator.)

Evaluate the balanced components: balance-unbalance conversion

Balanced components have two operation modes: differential mode and common mode. Balanced components need to be evaluated with respect to these two operation modes for complete characterization. A hybrid balun transformer, as shown in figure 4, enables the evaluation of both differential and common mode characteristics of a balanced component, used with a conventional (single-ended) network analyzer. In practice, this hardware approach induces measurement errors caused by the non-ideal characteristics of actual hybrid balun transformers, which cannot be removed because there are neither calibration standards nor a standard error correction methodology for balanced circuits. More commonly used are simple balun trans- formers that only transfer differential mode signals. This approach obviously does not show the common mode characteristic of the components. The non-ideal characteristics of the balun transformers induce measurement errors, and further measurement errors are caused by the common mode signal that is reflected at the balun transformer.
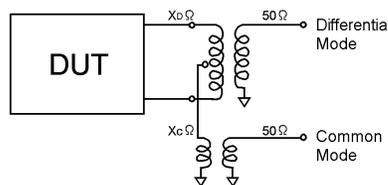
Figure 4. Hybrid balun transformer for balanced port evaluation

The fixture simulator provides more accurate measurements by mathematically converting the single-ended measurement parameters into balanced parameters, which can be described as the embedding of the ideal hybrid transformer. This conversion uses the same algorithms as that used in the de-facto market standard of Agilent's N444X Balanced-measurement systems. The software approach than hardware one is not only more accurate but also more flexible in that the users can set the differential and common mode characteristic impedance arbitrarily. (Note that the characteristic impedance can be specified with a positive real number in the fixture simulator.)

The fixture simulator, following the Agilent N444X systems, employs mixed-mode S-parameters in order to describe the characteristics of balanced components. Mixed-mode S-parameters are the same as conventional (single-ended) S-parameters in that the parameters are defined as the ratio of the response and incident normalized power waves. The only difference, in mixed-mode S-parameters, is that the signals are mode specific, namely differential mode and common mode. Figure 5 shows how a set of mixed-mode S-parameters for two-balanced port component is described in a matrix form. Mixed mode S-parameters can also be used in the same way when balanced ports and single-ended ports coexist. The simplest case where a component has a single-ended port and a balanced port is given in figure 6.
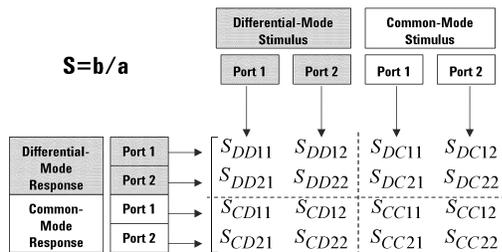
$$S = b/a$$

$$\begin{bmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\ S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\ S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22} \end{bmatrix}$$

Figure 5. Mixed-mode S-parameters for a two-balanced port component

$$\begin{bmatrix} S_{SS11} & S_{SD12} & S_{SC12} \\ S_{DS21} & S_{DD22} & S_{DC22} \\ S_{CS21} & S_{CD22} & S_{CC22} \end{bmatrix}$$
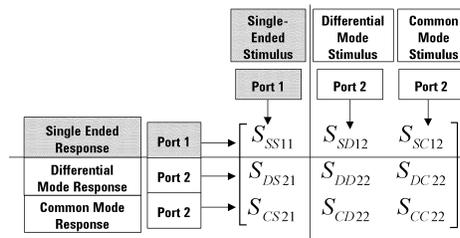
Figure 6. Mixed-mode S-parameters for a component with a balanced port and a single-ended port

The actual measurement results of a single-ended to balanced SAW filter using the ENA Series network analyzer are shown with single-ended S-parameters and mixed-mode S-parameters in figure 7 and figure 8 respectively. The mixed-mode S-parameters show useful insight into the characteristics of the SAW filter when it is used in a balanced circuit, while the single-ended parameters are very difficult to be related with the balanced operation of the filter. In the mixed-mode S-parameters, the port matching of the single-ended and differential ports are given as S_{SS11} and S_{DD22} respectively. S_{DS21} shows the desired forward transmission performance (single ended input to differential output), while S_{CS21} shows the generation of unwanted common mode signal in the forward transmission, which can be the source of EMI radiation. It is worth noting that the single-ended transmission measurements (S_{21} and S_{31}) show the stop band rejection of around 40 dB that is significantly smaller than the differential mode rejection of around 60 dB shown in S_{DS21}.
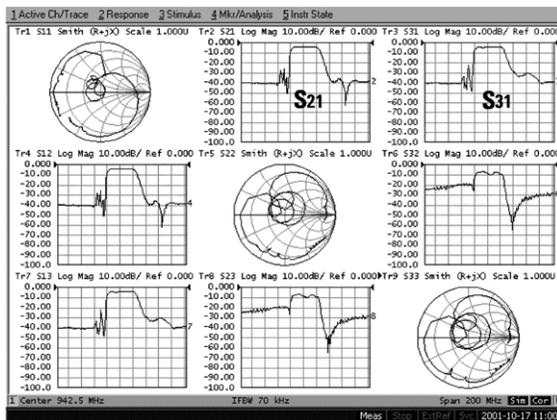

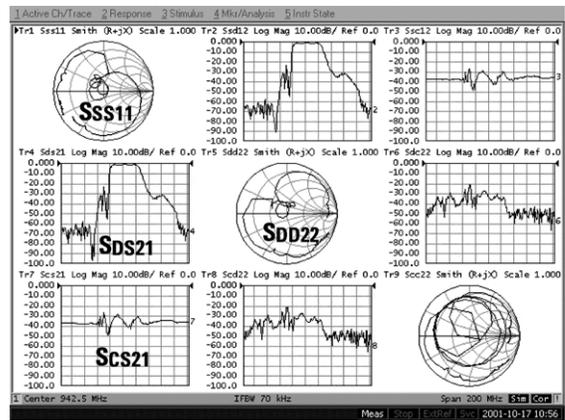**Figure 7. SAW filter measurement result with single-ended S-parameters**

Figure 8. SAW filter measurement result with mixed-mode S-parameters

Besides the fixture simulator, there are two other notable features of the ENA Series that contribute to balanced measurement. They are the two receivers per measurement port architecture, and full N-port calibration capability of up to four ports. The architecture is very effective for measuring balanced components, which are inherently multi-port and require full N-port measurement (N^2 S-parameters): balanced components have at least three ports, if all device terminals are counted as single-ended ports. The ENA Series network analyzer measures all of its measurement ports simultaneously as each measurement port is equipped with two receivers, which drastically reduce the number of sweeps compared to the conventional network analyzers that can measure only two ports at the same time. In case of full four-port measurement, the ENA Series network analyzer requires only four sweeps, while the conventional one sweeps twelve times. Full N-port calibration ensures adequate accuracy for balanced measurement when components are measured with a multi-port network analyzer. As a result, the ENA Series network analyzer achieves the unprecedented speed of the accurate balanced component measurement.

Reference 3) Agilent application note 1373-2B provides discussion on how to interpret mixed-mode S-parameters. For a rigorous treatment of the development of mixed-mode S-parameters, see reference 4) Bockelman, et al.

www.agilent.com/find/ena

8

Evaluate the component characteristics with virtual external circuits: matching circuit embedding

RF components are usually used within a larger circuit, and RF engineers are sometimes required to evaluate the total characteristic of the component when it is connected to external circuits, such as impedance matching circuits. The fixture simulator converts the measured S-parameters as if the component were equipped with the user-defined embedding circuits, which substantially decrease the evaluation work compared to the actual implementation of the external circuits. Typical matching circuit topologies are available within the fixture simulator for easier circuit definition. The network embedding is available for both single-ended measurement and balanced measurement as described below:

In single-ended measurement, the users can specify an embedding circuit for each of the measurement ports by using the pre-defined matching circuit topologies listed in figure 9, in which the values of the lumped circuit elements can be set arbitrarily. For more compli-cated circuit embedding, the fixture simulator accepts any network described in the 2 x 2 S-parameters Touchstone format (.s2p).
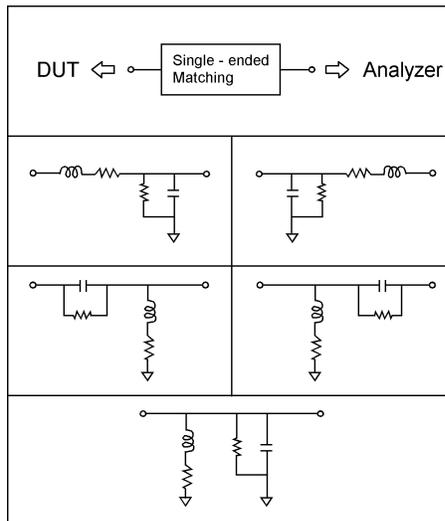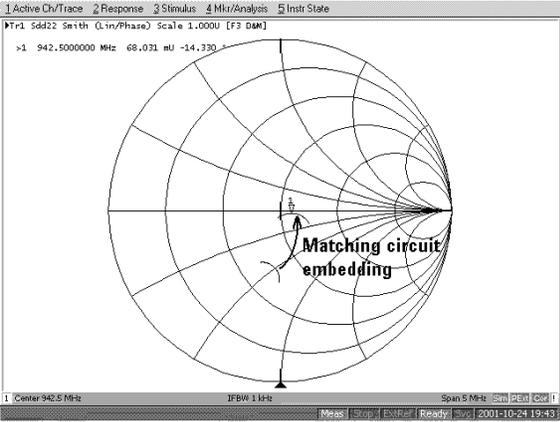

Figure 9. Single-ended matching circuit topologies

In balanced measurements, in addition to the single-ended circuits described above, a differential matching circuit can be embedded in each differential port, using a shunt L–shunt C topology, as shown in figure 10. A differential embedding circuit can be also defined with a Touchstone file similar to single-ended circuit embedding.
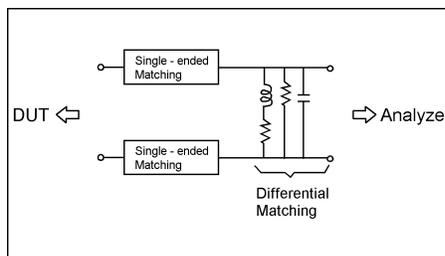
Figure 10. Differential network embedding

www.agilent.com/find/ena

9

Figure 11 shows the effect of the matching circuit embedding in the single-ended to balanced SAW filter measurement. The filter is designed to be used with the differential matching inductance of 56 nH, and the figure shows that the differential port matching improves when the matching circuit is (mathematically) embedded to the measured circuit.

Figure 11. The effect of the matching circuit embedding in single-ended to balanced SAW filter measurement

Conclusions

The fixture simulator of Agilent ENA Series network analyzers is a powerful, yet easy to use, tool for data processing on measured S-parameters. The fixture simulator performs complicated data processing necessary for various RF applications, which would normally require an external computer calculation. It has two fundamental advantages over conventional solutions: firstly the processing speed is faster because the entire process is completed within the analyzer firmware. Secondly, the operation is simplified as the function is realized as a part of the network analyzer.

In production test, the fixture simulator, together with the fast sweep speeds of the ENA Series, enables more complete measurements that would never be accepted in conventional solutions due to the speed limitations. For example, mixed-mode S-parameters analysis has not been accepted in production, as it has been considered too slow. More complete testing contributes to higher production yields thus lowering the cost of test per device. As to engineering use, the easy to use operation of the fixture simulator improves engineering productivity: RF engineers can perform various complex simulations as easily as if they were performing normal S-parameter measurements.

References

1. De-embedding and Embedding S-Parameter Network Using a Vector Network Analyzer, Agilent Application Note1364-1

2. Characterizing Differential Devices and Circuits Using Agilent's Balanced Component Measurement Solutions - Overview, Agilent Application Note 1373-2A

3. Characterizing Differential Devices and Circuits Using Agilent's Balanced Component Measurement Solutions – Understanding Mixed-Mode S-Parameters, Agilent Application Note 1373-2B

4. Bockelman, D.R., Eissenstadt, W.R., *Combined Differential and Common-Mode Scattering Parameters: Theory and Simulation* IEEE Transactions On Microwave Theory and Techniques, Vol. 43, No. 7, July 1995

www.agilent.com/find/ena

Agilent Technologies' Test and Measurement Support, Services, and Assistance

Agilent Technologies aims to maximize the value you receive, while minimizing your risk and problems. We strive to ensure that you get the test and measurement capabilities you paid for and obtain the support you need. Our extensive support resources and services can help you choose the right Agilent products for your applications and apply them successfully. Every instrument and system we sell has a global warranty. Support is available for at least five years beyond the production life of the product. Two concepts underlie Agilent's overall support policy: "Our Promise" and "Your Advantage."

Our Promise

"Our Promise" means your Agilent test and measurement equipment will meet its advertised performance and functionality. When you are choosing new equipment, we will help you with product information, including realistic performance specifications and practical recommendations from experienced test engineers. When you use Agilent equipment, we can verify that it works properly, help with product operation, and provide basic measurement assistance for the use of specified capabilities, at no extra cost upon request. Many self-help tools are available.

Your Advantage

"Your Advantage" means that Agilent offers a wide range of additional expert test and measurement services, which you can purchase according to your unique technical and business needs. Solve problems efficiently and gain a competitive edge by contracting with us for calibration, extra-cost upgrades, out-of-warranty repairs, and on-site education and training, as well as design, system integration, project management, and other professional services. Experienced Agilent engineers and technicians can help you maximize your productivity, optimize the return on investment of your Agilent instruments and systems, and obtain dependable measurement accuracy for the life of those products.

By internet, phone, or fax, get assistance with all your test and measurement needs.

Online Assistance
www.agilent.com/find/assist

Phone or Fax
United States:
(tel) 1 800 452 4844

Canada:
(tel) 1 877 894 4414
(fax) (905) 282 6495

China:
(tel) 800-810-0189
(fax) 1-0800-650-0121

Europe:
(tel) (31 20) 547 2323
(fax) (31 20) 547 2390

Japan:
(tel) (81) 426 56 7832
(fax) (81) 426 56 7840

Korea:
(tel) (82-2) 2004-5004
(fax) (82-2) 2004-5115

Latin America:
(tel) (305) 269 7500
(fax) (305) 269 7599

Taiwan:
(tel) 080-004-7866
(fax) (886-2) 2545-6723

Other Asia Pacific Countries:
(tel) (65) 375-8100
(fax) (65) 836-0252
Email: tm_asia@agilent.com

Product specifications and descriptions in this document subject to change without notice.

Agilent Technologies