Multiport and Balanced Device Measurement Application Note Series

An Introduction to Multiport and Balanced Device Measurements

Application Note 1373-1

Introduction

The increase in integration in the wireless communications and electronics industries in recent years has been relentless. The need to decrease size, cost, weight, and power consumption is driving design engineers to replace discrete components with more complex modules. This is leading to component level integration on a single substrate. Such modules have multiple RF paths through them and multiple terminal connections that must be measured together as a complete unit.

This application note is an introduction to alternative methods and special test considerations for making accurate measurements on devices with more than two terminal connections.

Agilent Technologies

What are multiport and balanced devices?

Very simply, a multiport device is any network with more than a single input and a single output. A common application for such a passive network is to separate, divide, or filter RF signals that pass through them between multiple outputs. A common example of a three-port device used in every cordless or wireless phone is a diplexer. A diplexer is two filters that share a common node. Most are commonly known as duplexers because they enable simultaneous transmission and reception of RF signals at different frequencies. Other representative multiport devices include couplers, power dividers, circulators, some SAW filters, and antenna switch modules. Each port on a connectorized RF device is comprised of two terminals. When one terminal connection is used to transmit the RF signal and the other is used as a ground reference, the port is referred to as single-ended. Traditionally, most RF devices have been designed to operate in this mode.

When a terminal is designed to reference a signal on another terminal, it is operating in a differential mode. The terminal pair is known as a differential or balanced port. These circuits are designed to have a pair of electrically symmetrical signal paths. Signals are transmitted through the device 180 degrees out of phase with respect to one another. Any signal that is common or in-phase to both terminals will ideally be rejected, and will not pass through the circuit. This characteristic gives the device a lower susceptibility to electromagnetic interference (EMI). For this reason differential circuits and transmission lines have been used at low frequencies for many years. Accurately measuring the magnitude and type of signal that passes through these circuits can be a challenging undertaking. A good example of a passive balanced circuit is a SAW filter that has been designed to have a combination of balanced and single-ended input or output ports. Differential devices cannot be easily tested with a traditional two-port network analyzer. Both differential and single-ended multiport devices need more physical connections to the test instrumentation, and both have similar test setup requirements. Because of these requirements, balanced devices are generally considered a subset of the multiport-device category. Figure 1 shows a common block diagram for an antenna switch module (ASM) that has both single-ended and balanced ports. The analysis of this network presents some unique challenges.

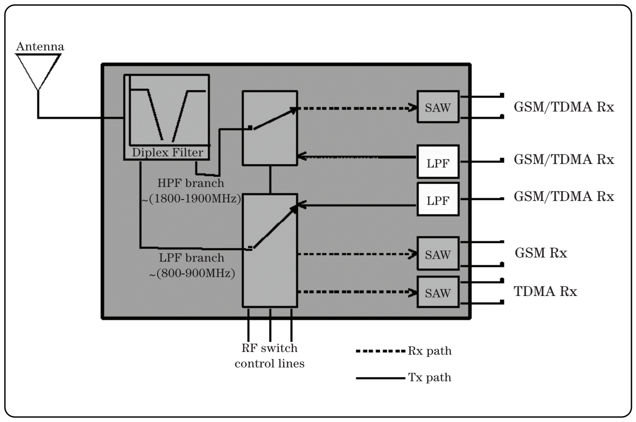

Figure 1: Tri-band antenna-switch module with balanced and single-ended ports

Characterizing multiport networks with S-parameters

Scattering parameters, more commonly known as S-parameters, are the widely accepted way of characterizing the linear response of high frequency networks. The same advantage S-parameters have for two-port networks holds true for multiport and balanced networks with a few additions. For a two-port network the familiar S_{12} and S_{21} are a measure of the complex insertion loss or gain through the device. The reflection parameters, S_{11} and S_{22}, are measures of the input and output mismatch loss respectively. The S-parameter matrix of a multiport network must be expanded to n^2 elements, where n is the number of network ports. Figure 2a shows the nine-term S-parameter matrix for the common three-port duplexer illustrated in figure 2b. Notice that the insertion loss terms have increased to six and the reflection terms to three. Since it is desired that no signal pass between ports 2 and 3, these S-parameters are referred to as isolation terms. As dimensionless expressions of loss and reflection, the S-parameters not only give a clear and meaningful physical interpretation of a network performance, but also form a natural set of parameters for use with signal flow graphs[1]. Figure 3 shows the flow graph for this three-port network. In a signal flow graph, each port of the network being examined is represented by two nodes. Signals entering the device from outside the network will enter at the a_n nodes and signals leave the network through the b_n nodes, where "n" designates the port number. The complex scattering coefficients are then represented as multipliers on the branches connecting the nodes within the network. These scattering coefficients travel from "a" nodes to "b" nodes in the direction of the arrows. Flow graphs can be used to graphically visualize the signal flow between ports of a network and simplify its analysis.

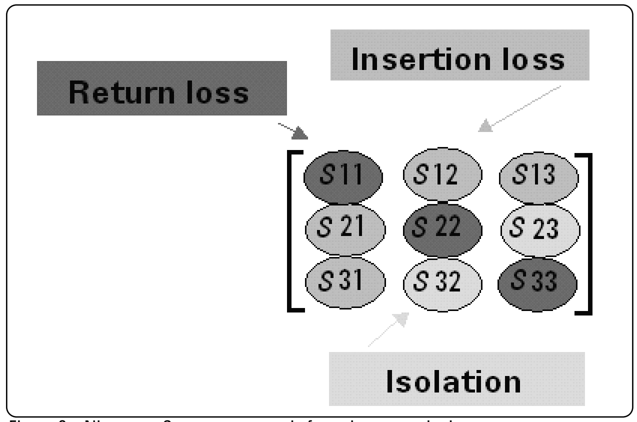

Figure 2a: Nine-term S-parameter matrix for a three-port duplexer

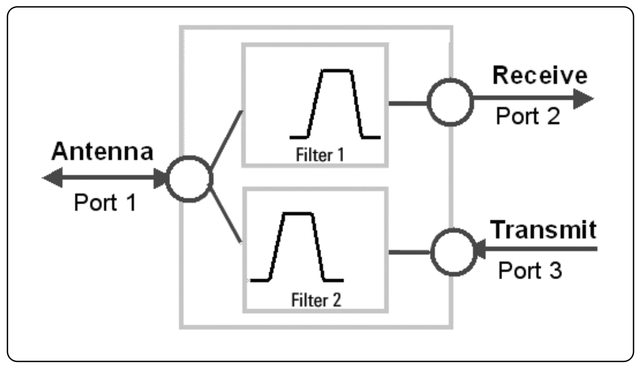

Figure 2b: Common three-port duplexer

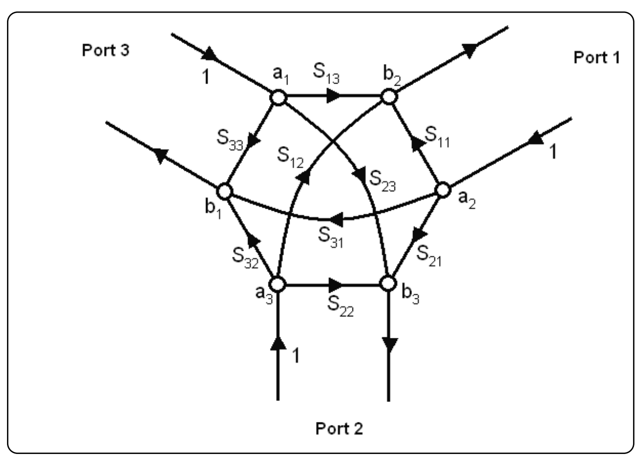

Figure 3: Flow graph for the three-port network

The single-ended S-parameter matrix can be misleading, or at best difficult to interpret, for circuits with balanced ports. The S-parameter definition needs to be expanded to independently consider each mode in which a balanced device will operate. As in single-ended S-parameters, the voltages and currents defined on the balanced ports can be used to define a set of normalized power waves. The difference is that these new mixed-mode normalized power waves are now mode specific. By again taking a ratio of the normalized response and incident power waves, a set of mixed-mode S-parameters can be defined[2]. This method considers each port to consist of a pair of terminals. With mixed-mode S-parameters a differential-mode stimulus is presented on the differential port terminal pair and the corresponding differential- and common-mode responses are measured on all of the device ports. Likewise a common-mode stimulus is presented to the same port and the differential- and common-mode responses again are measured. Conceptually the 4x4 matrix shown in figure 4a can be sub-divided into four quadrants that symbolize four separate modes of operation: DD, CC, CD, and DC. Each quadrant gives the input and output reflection characteristics and the forward and reverses transmission characteristics for that mode.

The differential-mode (DD) quadrant, in the upper-left corner of the mixed-mode S-parameter matrix, describes the behavior of the circuit with a differential stimulus and differential response.

The common-mode (CC) quadrant, in the lower-right corner describes the behavior of the circuit with a common-mode stimulus and common-mode response. By comparing the differential gain from the DD quadrant to the common-mode gain of the CC quadrant, the common-mode rejection ratio (CMRR) can be determined. The differential-to-common-mode-conversion (CD) quadrant, in the lower-left corner, describes the behavior of the circuit with a differential stimulus and common-mode response. In an ideal balanced device, these terms are all equal to zero, that is, there is no mode conversion. In practice, there will be some amount of mode conversion. The more mode conversion from differential-mode to common-mode that exists, the more likely there will be EMI radiation from the system or undesired ground loops generated.

The common-mode-to-differential-conversion (DC) quadrant, in the upper-right corner, describes the behavior of the circuit with a common-mode stimulus and differential-mode response. Again, in an ideal balanced device, these terms are all equal to zero, that is, there is no mode conversion. In practice, there will be some amount of mode conversion. The more mode conversion from common-mode to differential-mode that exists, the more susceptible the system will be to common-mode noise, either as ground noise or EMI.

Circuits with both balanced and single-ended ports can be described in a similar manner. To define the S-parameters of such a device, three modes must be included: single-ended mode for the single-ended port, which is specified as port one in this example, and differential and common-modes on the balanced port, which is port two. Referring back to figure 4a, the port-one terms with a differential stimulus or response automatically drop out of the matrix. The common-mode stimulus or response terms change to single-ended. The remaining nine terms are regrouped to make it easier to read as shown in figure 4b.

The full characterization available when mixed-mode analysis is used helps designers to reduce mode conversion, improve symmetry, and take full advantage of the enhanced performance that differential devices have to offer.

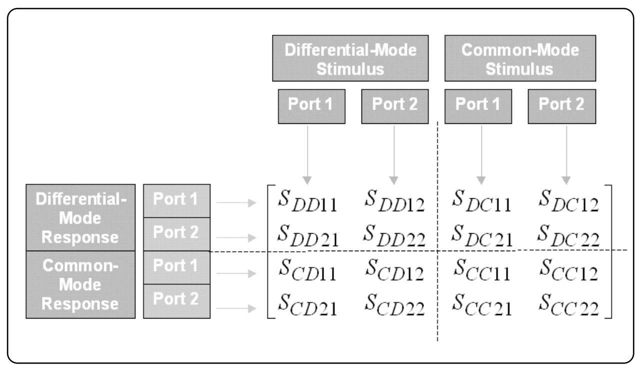

Figure 4a: Four-port balanced to balanced S-parameter matrix

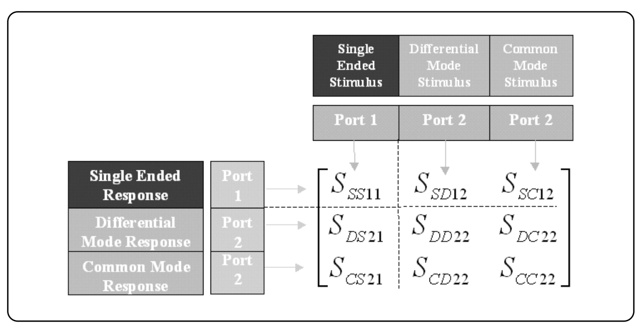

Figure 4b: Three-port single-ended to balanced S-parameter matrix

Methods for measuring multiport networks

Traditionally, network analyzers are comprised of two test ports that connect to a device under test. A full S-parameter network analyzer can deliver a single RF stimulus in both the forward and reverse directions. Since both singled-end and differential multiport devices have more then just two connections, designing and testing them using a traditional network analyzer can be complex. Both single-ended and differential devices have a number of alternative ways they can be tested. The four primary alternatives for measuring single-ended devices are examined first.

Single-ended alternatives

Most simply, a two-port network analyzer can be used to make a series of measurements on a multiport device. This method requires the device to be connected and reconnected multiple times and multiple two-port measurements made to obtain all the needed S-parameters. This is a very cumbersome procedure, especially as the number of device ports increases. Since only two ports are in the measurement path, the remaining ports on the device are not connected to the network analyzer. If the port is left open, a signal would be reflected by the open port and cause an error signal to enter back into the measurement path. Any unconnected ports must therefore be properly matched with an ideal load for this signal to have minimal effect. Figure 5 shows two isolation measurements of a cellular handset duplexer made on a E8358A PNA Series Network Analyzer. The isolation between the transmit and receive passbands is almost 10 dB better than it appears when the antenna port is not terminated with an ideal load. Understanding the effect of and minimizing error signals is the single most important issue in accurate multiport measurements. Another disadvantage of this test method is the inability to measure all of the device paths at once. For proper tuning of a duplexer, both the transmit and receive paths need to be visible simultaneously since tuning one path often affects both because there is coupling between them.

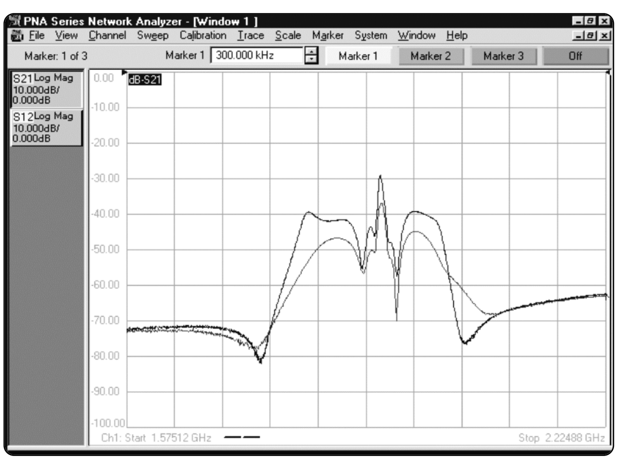

Figure 5: Isolation measurement with open and loaded duplexer third port

Another alternative for equipping a two-port network analyzer to measure multiport devices involves adding external switches in the measurement path. This allows each port of the device to be connected a single time and the test ports of the analyzer toggled between all measurement paths. An external power supply and control logic controlled by an external computer are needed to coordinate the switching and measurements. In addition, since the analyzer truly only has two ports, it is up the user to remember which measurements correspond to which S-parameter since the analyzer will use the same S-parameter annotations over again. Each switch will have its own unique losses so a separate two-port calibration needs to be preformed for each measurement path. To do so, multiple channels or instrument states must be used and recalled. This is not a trivial configuration to implement and use efficiently and accurately.

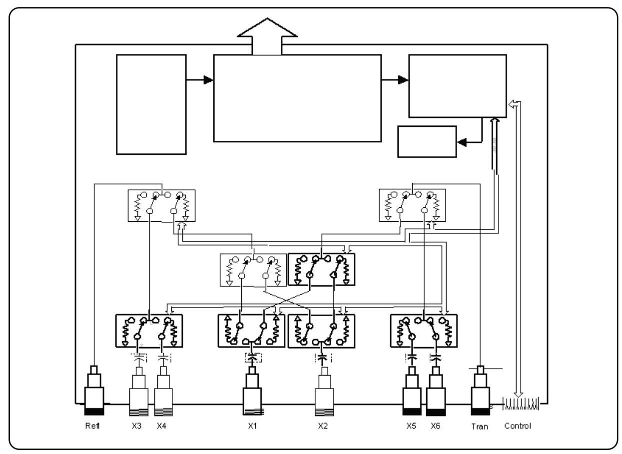

Figure 6: Z5623A H45 switch-matrix block diagram

It is often easier to integrate high-quality switches in a fixed external test set that can be connect directly to a two-port network analyzer. Advanced analyzers have firmware features built-in to manage the control of such external test sets that extend the flexibility of the standard instrument. A software program can be used to control the setup of the measurement paths and the calibration, as well as switching during measurement. The internal switch architecture of external test sets may vary. Just because a test set has enough ports to connect to every port on a device under test does not necessarily mean that all port-to-port measurements are possible. Figure 6 shows the block diagram of the Z5623A H45 external switching-matrix test set designed to work with the PNA series network analyzers. With this switch configuration measurements are not possible between ports X3 and X4 nor between ports X5 and X6. It is often more beneficial to only provide internal measurement paths between a known set of measurement paths. With less internal switches costs are reduced and there is also less insertion loss through the test set. The limitation is that such a configuration is not as flexible for testing a variety of devices.

A system that can create a path internal to the test set between any two of its test ports is referred to as full crossbar. Both mechanical and solid-state switches can be used, each with distinct advantages. Solid-state switches offer faster switching speed, better repeatability, and infinite lifetime. This makes them ideal for the manufacturing environment. They also have higher loss, which will decrease the overall dynamic range of the system. Mechanical switches have less loss, better match, and can handle higher RF power levels. Due to their mechanical nature they have a finite life cycle, typically five million cycles. They are suitable for applications where high dynamic range is needed in a low-volume manufacturing or R&D environment.

The important specifications to consider when selecting a switch-matrix test set are return loss for each active and inactive port, insertion loss, crosstalk and isolation. It is important to understand what each of these specifications mean and how they will affect the measurements being made. The return loss performance has a similar affect as the load and source match specifications common to network analyzers. This is the indication of the level of signal incident to a test set port that will be reflected back into the measurement. When a two-port network analyzer is used with a switch-matrix test set this concept is easy to visualize. There is a single measurement path between the stimulus of one port and the receiver of the other port. Two of the ports on the test set are active at once. All other ports are inactive. As the internal switches of the test set change and a new measurement path is established the active and inactive ports change. This is important because only the ports actively making measurements are the corrected ports. The inactive ports are out of the correction and are terminated internally with loads. For this reason inactive ports will have a different return loss specification than the active ports. When a three-or-more-port network analyzer is used with an external test set the principles are the same, but more complex. It can no longer be said that there is a single measurement path through the device, because multiple receivers are making measurements simultaneously. There are now multiple active ports in the correction. Any remaining ports are inactive and do not have any correction applied to them. The insertion loss specification is simply the loss from the analyzer to the ports of the test sets. This will affect the overall dynamic range of the system. The last two specifications of importance are crosstalk and isolation. They are both a measure of the internal signal leakage. Isolation is measured by placing a short circuit on each port of the test set and measuring the signal level that is coupled to the receiver. Crosstalk is calculated by adding the isolation to the forward and reverse return loss of the test set. One disadvantage of using a switch-matrix test set is that they generally require more measurement sweeps to obtain all the S-parameters. For many applications all possible S-parameters do not need to be measured and switch-matrix test sets provide the needed performance.

The problem of excessive sweeps is eliminated by test sets that have a measurement receiver for each port. Figure 7 shows the block diagram of the four-port ENA Series network analyzer. Its unique architecture incorporates a measurement and reference receiver at each port to optimize high-speed multiport measurements. Multiple transmission measurements can be made simulatneously because there are no switches between the port and the measurement receivers. Since all four ports are active at once the number of sweeps required to measure all S-parameters is reduced to a single forward sweep for each port. Consider a four-port device that could require between eight and 12 sweeps using an external switch-matrix test set, which will now only require four. This type of test set is most often internally integrated in the network analyzer itself. This integration makes it the most elegant and easiest to use because the firmware is designed around the full feature set that the hardware can deliver. Many of the tricks that need to be made to keep S-parameters straight with other setups will be eliminated. This can make multport measurements as easy, accurate, and efficient as any two-port device measurements.

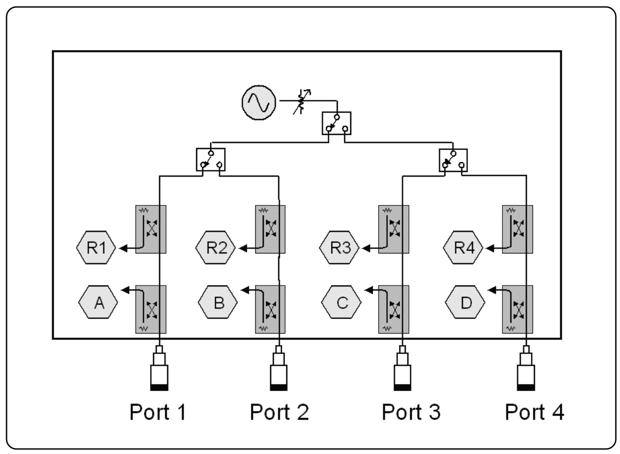

Figure 7: ENA receiver-based test set block diagram

Balanced alternatives

The traditional approach to characterizing balanced devices is to convert each balanced pair to a single-ended port by placing a balun in the measurement path. Measuring a device through a balun limits the accuracy of the measurement. Loss, amplitude balance, phase balance, and isolation of the balun must all be known and error correction applied. In addition, the relatively narrow bandwidth of the balun limits its practicality, particularly when characterization over a wide frequency range is needed. Finally, baluns do not allow for a complete characterization of the device. Referring back to figure 4a, only the differential quadrant of the mixed-mode S-parameter matrix can be measured this way. With the balun method, information regarding the common-mode performance, including common-mode rejection ratio (CMRR) and the mode conversion behavior of the device is lost and common-mode effects cannot be corrected in the measurements. These considerations limit the use of baluns for characterizing balanced circuits.

Two main alternatives for characterizing the full mixed-mode S-parameter matrix exist. A system having two RF sources that can be locked 180 degrees out of phase, often referenced as a pure-mode vector network analyzer (PMVNA), can be used. This PMVNA would provide the device under test with differential-mode and common-mode signals and measure the mixed-mode S-parameter matrix created directly from these measurements. If such a system is constructed it must have very good phase stability, typically less than one degree variation at the calibration plane. Such a setup is further limited because traceable calibration standards for balanced systems do not exist, and a standard error correction methodology for balanced circuits has not been widely accepted.

A more practical method has been developed based on the superposition theory of linear networks. This calculated mixed-mode method takes a series of single-ended measurements on each port and mathematically calculates the complete differential and common-mode response of the network. Such a method can utilize traceable single-ended calibration standards and four-port error correction calculations. Several products are currently on the market using this calculated mixed-mode S-parameter method. This method yields all four quadrants of the mixed-mode S-parameter matrix. For a complete review of the alternatives for making differential measurements see Agilent Application Note 1373-2, *Concepts in Balanced Device Measurements*.

Calibration and error correction

Calibration and error correction are two of the most important topics to understand when making network analyzer measurements. No test hardware is perfect, so some process is required to improve the performance. Calibration is the process of measuring high-quality standards and comparing their response with the known response for the standard[3]. All measurements made with the same test setup will show this same deviation. This information can be used to calculate a set of correction terms that will be used on all future measurements to remove the imperfection in the system. There are three different types of errors that are present during network analyzer measurements. They are systematic, random, and drift errors. Systematic errors can be corrected through the calibration and error correction process. Random errors cannot be predicted and therefore cannot be corrected for. Drift errors are cause by changes to the test setup after calibration, primarily due to temperature variations, and can be corrected by re-calibrating. There are six different types of systematic errors. Two errors are caused by signals leaking between the source and receivers without traveling through the device under test. They are called the directivity and isolation error signals. Two errors deal with the imperfect impedance match of the input ports and are called source and load match errors. The last two error terms describe the frequency response errors of the system and are the reflection and transmission tracking errors. For a two-port system these six error signals are present in the forward and reverse directions. In order for a corrected measurement to be made, all four S-parameters of the two-port device need to be measured. Both the six error terms from the forward direction and the six from the reverse measurement are used in the error correction calculations; hence this is called the twelve-term error model. As the number of device ports increases the total error terms will also increase by $3 \times n^2$ where "n" is the number of ports. In order to calculate an n-port error corrected measurement, all n^2 S-parameters must be measured and $3 \times n^2$ error terms used in the equations to solve for the corrected S-parameter values.

Many multiport systems using external test sets offer only standard two-port error correction. In such a configuration only the errors caused by the two active ports can be corrected for and removed from the measurement. Figure 8a is a flow graph illustration of the S_{23} isolation measurement of the three-port duplexer shown in figure 2b. The desired S_{23a} measurement is shown by the dark solid line. S_{23m} is the measured response from the transmit to receive ports. It is the combination of the S_{23a} (actual) and all the error signals present. The four error signals, E_{s33}, E_{x32}, E_{L23}, E_{t23}, in figure 8b will affect the measured result. When a two-port calibration is used, ports 3 and 2 are the active ports and the effects of these four error terms are removed from the results though the error correction process. However, some signal will leak between ports 3 and 1. This signal, illustrated by the dotted lines, will be reflected by the raw load match of port 1 and travel through the device to port 2 and be detected. A system using a two-port calibration has no way of correcting for the additional effect of E_{L13} and it will add to the measurement uncertainty. In contrast, a full three-port error corrected measurement will correct for all the error terms for this transmission measurement and give the most accurate results. In order to perform these calculations, all nine S-parameters must be measured and 27 error terms used in the calculations. Figure 8c shows all nine S-parameters and the nine error terms present when a stimulus is applied to port 3. Additionally, nine different error terms are present when the stimulus is moved to each of the other ports.

Calculated mixed-mode S-parameter measurements need the highest level of accuracy available. Any inaccuracies in the measurement data will be increased by the mixed-mode calculations. It is not practical therefore to make these calculations from single-ended measurements without full n-port error correction. Calibration can be the most time consuming and repetitive part of making multiport measurements, but without it measurement uncertainties may be so large that the results are meaningless.

There are several ways of performing a calibration on a multiport system. For some systems, a series of two-port calibrations need to be performed between every port pair of the measurement path. This is even more repetitive and time consuming when mechanical standards are used. Many of the ports will be measured multiple times. A two-port electronic calibration standard can reduce this to a manageable amount of connections. Some systems have a time saving feature that only requires a single one-port calibration to be performed on each port and a thru measurement between all port-pair measurement paths. This type of system remembers the calibration standards measurements for each port and uses them for all the calculations without having to re-measure them each time. For a complete description of error correction for two-port network analyzer measurements, see Agilent Application Note 1287-3, *Applying Error Correction to Network Analyzer Measurements*.

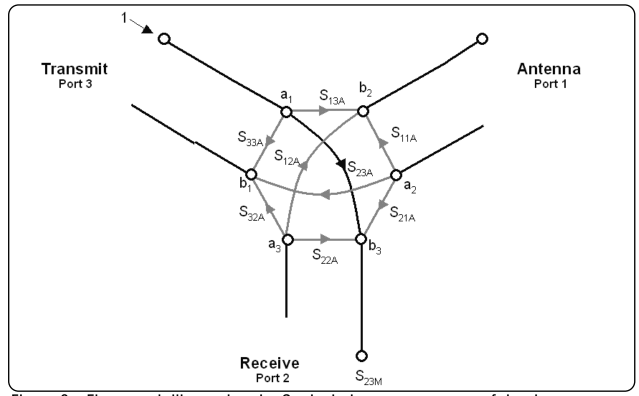

Figure 8a: Flow graph illustrating the S_{23} isolation measurement of the three-port duplexer shown in figure 2b

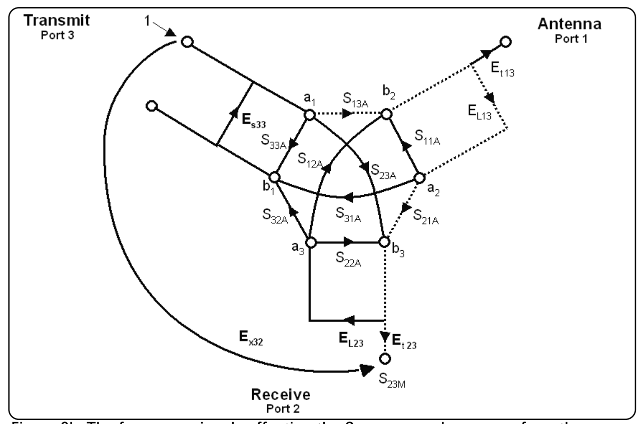

Figure 8b: The four error signals affecting the S_{23} measured response from the transmit to receive ports

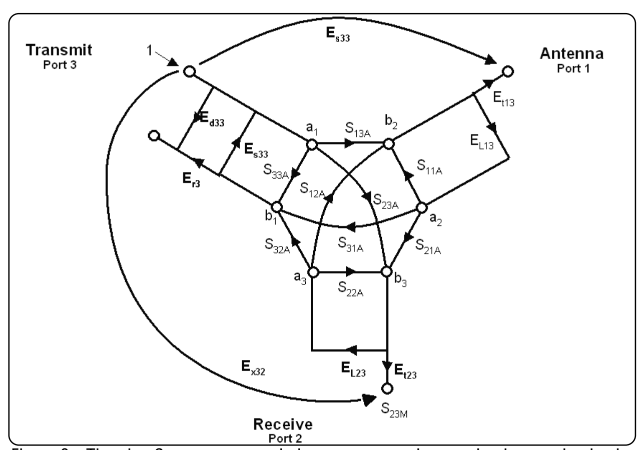

Figure 8c: The nine S-parameters and nine-error terms that result when a stimulus is applied to port 3

Selecting the right multiport solution

Since multiport devices can vary greatly in design and functionality, it may be challenging to select the best solution for a given application. It is good to consider how much measurement flexibility is needed in the system. Often it is most cost-effective in manufacturing to sacrifice the flexibility of a full crossbar system. Since the measurement paths for the device are predefined, a test set can be designed specifically to test that device. The level of uncertainty that is acceptable should be determined. Perhaps for the measurements being made, two- or three-port error correction is sufficient. Ease of use of the user interface is another aspect to be considered. Calibration procedure, measurement setup, how parameters are displayed, and how easy it is to export measurement data can all affect using the system on an everyday basis.

Conclusion

Multiport devices are becoming increasingly popular and widespread in communication systems. Modules are increasing in integration and complexity. It is important to understand the unique test challenges of such devices. Multiport test solutions offer three key benefits for testing these devices. They can improve measurement throughput by allowing multiple signal paths to be tested with a single connection. Multiport test systems provide the most complete picture of how a device will perform in actual operation. When tuning and testing duplexers this is especially useful because both paths can be viewed simultaneously. For differential devices, mixed mode S-parameters give insight into the common-mode that would be otherwise lost. And finally, multiport calibration allows multiport devices to be tested with the ease and accuracy of a two-port network analyzer.

Glossary of terms

Multiport device: Any device with greater than two ports.

Multipath device: A device with more than one signal path through it.

Single-ended: Referenced to a common ground.

Balanced or differential: Two signals referenced to each other.

Common-mode: Signal common to two differential terminals.

Full crossbar test set: Most flexible design because all port-to-port measurement paths can be established.

Switch-matrix test set: A test set designed to multiplex the test ports of a network analyzer between multiple device-measurement paths.

Related Literature

Concepts in Balanced Device Measurements, Application Note 1373-2, literature number 5988-5635EN

Applying Error Correction to Network Analyzer Measurements, Application Note 1287-3, literature number 5965-7709E

S-Parameter Techniques for Faster, More Accurate Network Design, Application Note 95-1, literature number 5952-1130 (see also the interactive Application Note 95-1 at www.agilent.com)

Agilent ENA Series 2, 3 and 4 Port RF Network Analyzers, Brochure, literature number 5988-3765EN

Agilent Introduction to the Fixture Simulator Function of the ENA Series RF Network Analyzers: Network De-embedding/Embedding and Balanced Measurements, Product Note, literature number 5988-4923EN

Agilent PNA Series RF and Microwave Network Analyzers, Brochure, literature number 5968-8472E

High Performance Testing of Wireless Handset Front-end Modules, White Paper, literature number 5988-4398E

Agilent Measurement Solutions for Balanced Components, Product Overview, literature number 5988-2186EN

Agilent 87050E 50-Ohm Multiport Test Sets, Brochure, literature number 5968-4763E

Key Web resources

For more information on Agilent's balanced solutions please visit:
www.agilent.com/find/balanced

Visit our component manufacturer industry area at:
www.agilent.com/find/component_test

References

[1] *S-Parameter Techniques for Faster, More Accurate Network Design*, Application Note 95-1, literature number 5952-1130

[2] D. E. Bocklemann and W. R. Eisenstadt, *Combined Differential and Common-Mode Scattering Parameters: Theory and Simulation*, IEEE Transactions on Microwave Theory and Techniques, Col. MTT-43, July 1995.

[3] *Applying Error Correction to Network Analyzer Measurements*, Application Note 1287-3, literature number 5965-7709E

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 onsite education and training, as well as design, system integration, project management, and other professional engineering services. Experienced Agilent engineers and technicians worldwide 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.

Agilent Email Updates

www.agilent.com/find/emailupdates
Get the latest information on the products and applications you select.

Agilent T&M Software and Connectivity
Agilent's Test and Measurement software and connectivity products, solutions and developer network allows you to take time out of connecting your instruments to your computer with tools based on PC standards, so you can focus on your tasks, not on your connections. Visit **www.agilent.com/find/connectivity** for more information.

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

Phone or Fax
United States:
(tel) 800 452 4844
Canada:
(tel) 877 894 4414
(fax) 905 282 6495
China:
(tel) 800 810 0189
(fax) 800 820 2816
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) 0800 047 866
(fax) 0800 286 331
Other Asia Pacific Countries:
(tel) (65) 6375 8100
(fax) (65) 6836 0252
Email: tm_asia@agilent.com

Online Assistance:
www.agilent.com/find/assist

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

Printed in USA *November 11, 2002*
5988-5634EN

Agilent Technologies