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Test Procedure for Measuring Transmission and Reflection

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1.0 PREFACE

The measurement of RF reflection and transmission spans several generations of test equipment. The fundamental components of these measurements are a sweep generator, a coaxial switcher, a directional coupler bridge, switchable attenuators, an RF amplifier, an RF detector and a scalable display.

The fundamental transmission measurement process is to generate an RF signal that sweeps through a user defined frequency range. This CW signal is routed through two paths by means of a coaxial spdt relay at each end of the two paths. One path is a reference that conducts the generator output through a reference attenuator directly to the detector. The other path travels through the device under test. As the signal alternates rapidly between the two paths, a differential image of the frequency response of the two paths is displayed. Measurements at each frequency are inferred by the difference between the two traces.

The same technique is applied to reflection measurements by inserting a directional coupler bridge in place of the device under test. The tap port of the bridge is connected to the device port to separate the incident from the reflected signals. The quality of the return loss measurement depends upon the directivity of the bridge.

This early method of measurement is scalar. This means that only the magnitude of the signal power is recovered on the display. Early network analyzers packaged these basic functions into one test instrument, and the use of internal microprocessors enabled a more accurate display of the difference between the reference and the device under test. Examples of early **scalar** network analyzers are Agilent 8711 and 8713.

However, the phase of the test signal is also important. The magnitude and phase define a complex data set at each test frequency that completely characterizes the behavior of a signal as it encounters an RF device. This requires an advanced layer of signal processing. A network analyzer capable of rendering the complex parameters of a waveform is called a **vector** network analyzer. Most of the early scalar network analyzers are now obsolete but the vector analyzer market has continued to evolve. These instruments have become widely accessible, and the complex output data is far more useful in applications from circuit and component design to manufacturing.

Therefore, while a scalar measurement approach to measuring return loss and insertion loss or gain is sufficient, a vector network analyzer is recommended for this generalized test procedure primarily because the results are far more applicable and the error correction capabilities enable greater measurement precision.

2.0 SCOPE AND DEFINITIONS

2.1 SCOPE

The purpose of this test procedure is to determine the reflection at any port, or the transmission between any two ports of a properly terminated device, as measured across a frequency range of interest. Depending on use of the data, return loss, insertion gain or loss, isolation, response variation or bandwidth can be derived. This specification is applicable to the testing of 75Ω devices.

2.2 DEFINITIONS

2.2.1 <u>S-Parameters:</u> Scattering parameters are a convention used to characterize the way a device modifies signal flow. S-parameters are always a ratio of two complex quantities. S-parameter notation identifies these quantities using the numbering convention S(out in) where the first number refers to the device port the signal is emerging from and the second number is the device port where the signal is incident. For example, the s-parameter S_{21} identifies the measurement as the complex ratio of the signal emerging at device port 2 to the incident signal at device port 1.

Figure 1 is a representation of the s-parameters of a two-port device. In the illustration, “a” represents the signal entering the device and “b” represents the signal emerging.

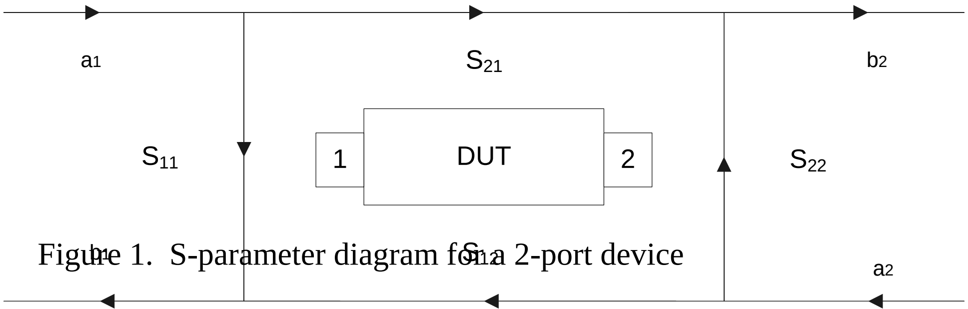

Figure 1. S-parameter diagram for a 2-port device

S-Parameter	Definition	Description	Direction
S_{11}	b1/a1 a2=0	Input Reflection	FWD
S_{21}	b2/a1 a2=0	Forward Transmission	FWD
S_{12}	b1/a2 a1=0	Reverse Transmission	REV
S_{22}	b2/a2 a1=0	Output Reflection	REV

Table 1. S-parameter definitions and descriptions

2.2.2 Return Loss: *Ratio between the level of a signal impinging on a port and the level of the signal reflected back from that same port.* Therefore, this is a one-port measurement. The s-parameter notation is S_{nn} where n is any port of the sample being tested. Literally, this is the definition of the VOLTAGE REFLECTION COEFFICIENT (r).

$$\mathbf{r = E_{reflected} / E_{incident}} \qquad \text{Eq. 1}$$

- $E_{reflected}$ = Voltage of the reflected signal
- $E_{incident}$ = Voltage of the incident signal

When this ratio is expressed in dB, return loss becomes

$$\mathbf{R/L = 20\ LOG_{10}[|1/r|] = 20\ LOG_{10}[E_{incident} / E_{reflected}]} \qquad \text{Eq. 2}$$

Return Loss may also be expressed in dB as the logarithm of the ratio of the measured impedance and a 75-ohm reference impedance since the signal power from the analyzer directed at the port is constant.

$$\mathbf{R/L = 20\ LOG_{10}[(Z1+Z0)/(Z1-Z0)]\ *} \qquad \text{Eq. 3}$$

**Valid when Z1>Z0*

- Z1 is the measured impedance (may be complex)
- Z0 is the reference impedance derived from calibration standard

2.2.3 Insertion gain or loss: Ratio between the level of a signal exiting a port of a device to the signal entering a port of a device. For passive devices this is called insertion loss since the signal emerging is less than the incident signal. In the case of an amplifier, this is called gain since the signal emerging is greater than the incident signal.

2.2.4 Isolation: The transmission response through a secondary path of a device typically having a higher attenuation than the primary path. For example, the path through two outputs of a splitter or the output and the coupled tap port of a symmetrical directional coupler has greater loss than the primary path from input to output.

In the case of an amplifier, the transmission response from output to input is the secondary path. The transmission response through this path is called reverse isolation.

2.2.5 Bandwidth: The frequency range that brackets the linear operation of a device. The endpoints of narrow band devices like filters are usually characterized by the frequencies where the transmission response has dropped by 3dB. The bandwidth of wide band devices like splitters, directional couplers and amplifiers is usually defined by a frequency response or flatness specification that applies to the boundary frequencies of the application.

2.2.6 Frequency response: The way that a device modifies the signal flow at each given frequency. This is often synonymous with flatness with respect to the transmission response.

2.2.7 Slope: *A measure of the monotonic frequency response of the network from low to high frequency. Slope is positive, or upward going, if the gain increases as the response is swept from low frequency to high frequency.* Slope can be derived numerically from the forward transmission data set. A linear trend line is constructed through the transmission data. It has the general form y=mx+b. Since it is linear, it is most representative of the overall slope response when it is derived from the linear portion of the response, not the endpoint frequencies.

A spreadsheet can apply the SLOPE function to the transmission response data. This yields 'm' in the equation for the trend line. Then the spreadsheet can apply the INTERCEPT function, which calculates the value 'b' where the trend line crosses the y-axis. From these two constants, the trend line is constructed as a set of data points of transmission vs. frequency. Multiplying the full frequency range by the factor m yields the value for the slope.

2.2.8 Flatness: *The maximum peak to valley excursion of the transmission response over the specified bandwidth.* The flatness can be derived numerically from the forward transmission data. Flatness is expressed as a ± tolerance around a line through the mean linear response. Once the trend line is established as a data set (see slope definition), the actual transmission data can be compared to it. The difference between the trend line and the response is computed for each frequency, and the spreadsheet applies the Min and Max function to this data set. This establishes the peak to peak deviation, which is then divided by 2 to yield a +/- value for the frequency response.

2.2.9 DUT: Device Under Test

3.0 <u>REFERENCES</u>

3.1 Informative References

ANSI/SCTE 96 2003 Cable Telecommunications Testing Guidelines

4.0 EQUIPMENT

Only equipment specific to this procedure is described in detail here. The Cable Telecommunications Testing Guidelines, ANSI/SCTE 96 2003, should be consulted for further information on all other equipment.

4.1 A vector network analyzer is recommended. Leading manufacturers of vector network analyzers are Agilent (HP), Anritsu (Wiltron), Advantest, and Rhode & Schwarz. The analyzer should have the following characteristics:

4.1.1 75 Ω impedance

4.1.2 Frequency range 5 MHz to 1002 MHz, minimum, with calibrated end points and markers available.

4.1.3 Capability of doing reflection, transmission or full two-port calibration to reduce the effect of analyzer test port mismatch and external component deficiencies.

4.1.4 Capability of interfacing with a printer or creating a data files for analysis of the test results.

4.2 Adapters and cables as required connecting the device under test to the measurement system. The impedance of all cables and adapters must be 75 Ω. Typical connector, cable and adapter sets are:

4.2.1 Agilent Model 8120-2408 Type N Cable, 75Ω; or equivalent

4.2.2 Agilent Model 11857B Type N Cable Set, 75Ω; or equivalent

4.2.3 Agilent Model 85036B 75 Ohm Type N Calibration Kit; or equivalent

4.2.4 Agilent Model 909E 75 Ohm Type N Precision Termination; or equivalent

4.2.5 Agilent Model 86211A 75 Ohm Type-F Adapter Kit; or equivalent

4.2.6 Agilent Model 85039A 75 Ohm Type F Calibration Kit;

4.2.7 Or equivalent products from other manufacturers.

4.3 Attenuators such as Agilent 86213A or equivalent as required for level and impedance matching with the following characteristics:

4.3.1 75 Ω impedance

4.3.2 Type-N 75 Ω connectors to match the test cables. N to F adapters to match the Device Under Test (DUT) if necessary.

4.3.3 At least 25 dB return loss (1.12:1 VSWR) from 5 MHz to 1002 MHz

5.0 SETUP

5.1 Follow any pre-calibration requirements recommended by the manufacturer for the network analyzer, including adequate warm-up and stabilization time. Ensure that the instrument is properly grounded and that anti-static precautions are maintained at all times. This includes an anti-static work surface and wrist strap that is grounded to the instrument.

5.2 Connect all necessary cables and adapters to the network analyzer including an in-line attenuator at the end of each test cable that connects to the test sample. A high quality in-line pad with an attenuation of 10dB is recommended to reduce measurement uncertainty from reflections within the setup. This is especially important when measuring low insertion losses or when the impedance of the device under test is reflective. A pad at the end of the test cable reduces the reflections between the device under test and the analyzer port.

5.3 Adjust the analyzer for the frequency range of interest, generally 5-1002 MHz. It is most convenient to select a frequency range such that the data points land on rational frequency values. For 801 data points, a frequency range of 5-1005 MHz will result in data at every 1.2 MHz interval.

5.4 Adjust the network analyzer power level suitable to the device under test.

5.4.1 Passive devices can usually tolerate higher power levels than active devices. Higher power levels will result in a lower measurement noise floor. Typical power levels for passives are 0dBm to 10dBm or 49dBmV to 59dBmV.

5.4.2 If there is a maximum input power level given for a particular device, the power level should be set so that the power at the reference plane does not exceed this value.

5.4.3 If there is a maximum output power level given for a particular device, the gain of the device must be factored into the input power level. The 1dB gain compression value or a graph of the output vs. input power of an active device is a good reference to consider when setting the power level.

5.4.4 Insure that the measurement power is within the linear operation of the device.

Note: In cases where low analyzer output power is required, some analyzers will have greater accuracy (less trace noise) if calibrated at a higher power, then the power is dropped for the measurement.

5.5 Select the s-parameter measurement relative to each channel

5.5.1 Set the measurement of channel 1 to forward reflection (S11).

5.5.2 Set the measurement of channel 2 to forward transmission (S21).

5.6 Select the display format for each channel. The usual selection is LOG MAG, which displays a Cartesian graph of signal level in dB versus frequency.

5.7 Select the other display characteristics to suit the measurement such as dual or single channel display, scale and reference levels of each channel, and any convenient markers.

5.8 With all of the functions of the analyzer optimally set for the particular test samples, proceed to calibration. A precision calibration kit as described in section 3 is required. This is an important step in minimizing systematic and repeatable errors introduced by the analyzer, the test cables, and the adapters. A full 2-port calibration is recommended since the instrument state can be saved to save setup time in the future.

5.8.1 It is important to note that when the user is prompted for particular calibration standards, the sex denotation refers to the test cable interface not the standard itself.

5.8.2 Refer to the calibration section of the network analyzer manual for other details that will serve to minimize measurement errors. Of particular interest is the issue of non-insertable devices. These have the same sex connectors on input and output ports. Many cable telecommunications products fall into this category.

5.9 Once the calibration procedure is complete, save the instrument state with the error correction coefficients to the internal non-volatile memory or to disk. As long as the physical setup components do not change, this instrument state can be recalled quickly. This means that these measurements can begin again following the instrument warm-up time. Instrument state recall also enables test sequencing where a series of different tests are performed using different measurement parameters such as frequency.

6.0 PROCEDURE

6.1 Overview

Network analyzers are generally two-port instruments although recent additions to the vector network analyzer market can have three or four ports. Alternatively, a switching matrix can extend the basic two-port analyzer to 4, 8, 12, or more for automated data collection in a production environment. In general, however, the characterization of an n-port device will be a combination of one and two-port measurements. This is illustrated in the earlier definition of the s-parameter system.

Reflection is a one-port measurement. Each port of a device will have one reflection measurement associated with it. Either port of the network analyzer is capable of making a reflection measurement. Some two-channel analyzers can measure the reflection of two ports simultaneously.

Transmission is a two-port measurement. The measurement is made through the device from one port to another. The measurement selection options offer either forward transmission from port 1 to port 2, or reverse transmission from port 2 to port 1. Some two-channel analyzers can measure forward and reverse transmission simultaneously. More advanced network analyzers have 4 channels that can display all four of the s-parameters of a two-port measurement simultaneously.

The data output of a standard two-channel vector network analyzer such as the Agilent 8714 will contain the s-parameters of the active channel. More capable instruments such as the Agilent 8753 can provide data for all four s-parameters in a single test. Since the post-processing of data via spreadsheet programs is an important consideration in the generation of reports or data files for design work, the data output capability of the analyzer used for these tests may have an impact on the test procedure sequencing.

In the following procedures for one-port and two-port measurements, it is assumed that the operator will insure that the setup procedure in section 4 is satisfied. The operator should also insure that anti-static precautions are taken at all times.

6.2 One-Port Reflection

6.2.1 Recall the instrument state defined in section 4 (setup).

6.2.2 Check to see that the measurement mode of channel 1 is set to forward reflection (S_{11}). The appropriate test cable will be connected to port 1 on the network analyzer.

6.2.3 Connect port 1 of the analyzer to the port of the DUT where a reflection measurement is to be made.

6.2.4 Terminate all other ports of the DUT with resistive 75Ω terminators having a return loss of greater than 25dB throughout the test frequency range.

6.2.5 Make use of the marker options to identify key features of the display such as maximums or minimums, delta relationships, or cornerstone frequencies.

6.2.6 Save the measurement for further analysis or report generation if necessary. Some of the options for saving the measurement are listed below.

6.2.6.1 Save to the display memory for comparison with subsequent measurements.

6.2.6.2 Save to a printer for a graphic record.

6.2.6.3 Save to a data file on a disk or an external computer. Consult the network analyzer manual for the most suitable file format options.

6.3 Two-Port Transmission

6.3.1 Recall the instrument state defined in section 4 (setup).

6.3.2 Check to see that the measurement mode of channel 2 is set to forward transmission (S_{21}).

6.3.3 Connect port 1 of the analyzer to the device port where signal is to be injected. Connect port 2 of the analyzer to the device port where the signal is to be measured.

6.3.4 Terminate all other ports of the device with resistive 75Ω terminators having a return loss of greater than 25dB throughout the test frequency range.

6.3.5 Make use of the marker options to identify key features of the display such as maximums or minimums, delta relationships, or cornerstone frequencies.

6.3.6 If the dual display option has been selected, the reflection and the transmission will be visible on the screen.

6.3.7 Save the measurement for further analysis or report generation if necessary. Some of the options for saving the measurement are listed below.

6.3.7.1 Save to the display memory for visual comparison with subsequent measurements.

6.3.7.2 Save to a printer for a graphic record.

6.3.7.3 Save to a data file on a disk or an external computer. Consult the network analyzer manual for the most suitable file format options.

7.0 APPENDIX 1 TEST METHOD FOR SPLITTERS

7.1 Recall the instrument state defined in section 4 (setup). Verify that the frequency range, power level and display properties are suitable to the device.

7.1.1 If the display properties are changed, the new state can be saved in another memory register without recalibration.

7.1.2 If the frequency range or power levels are changed, recalibration is recommended to maintain error correction accuracy.

7.1.3 If the cables or adapters are changed, recalibration is necessary.

7.2 Define a numbering system for the ports of the splitter beginning with the input as port 1.

7.3 Follow the test procedure defined above in section 5.3 for two-port transmission.

7.4 The following table lists the order of tests and cable connections required to make a complete set of s-parameters for a two-way splitter. The bold numbers are the splitter ports. It shows how nine data sets are derived from three tests.

Test #	NA port 1	NA port 2	Data			
1	1	2	S_{11}	S_{21}	S_{12}	S_{22}
2	1	3		S_{31}	S_{13}	S_{33}
3	2	3		S_{32}	S_{23}	

Table 2. Test sequence to completely characterize a 2-way splitter.

7.5 The following table lists the correlation between s-parameters and RF measurements. Since the splitter response is essentially the same in both forward and reverse directions, some of the s-parameters are redundant for report purposes.

R/L means Return Loss

IL means Insertion Loss

ISO means Isolation

Each cell in the matrix represents a 201-point data set of magnitude and angle vs. frequency.

S_{11} R/L in	S_{21} IL in--2	S_{31} IL in--3
S_{12} IL 2--in	S_{22} R/L 2	S_{32} ISO 2--3
S_{13} IL 3--in	S_{23} ISO 3--2	S_{33} R/L 3

Table 3. Matrix of all the 3-port S-parameters and corresponding splitter measurements.

7.6 The following table lists the order of tests and cable connections required to make a complete set of s-parameters for a three-way splitter. The bold numbers are the splitter ports. It shows how 16 data sets are derived from 6 tests.

Test #	NA port 1	NA port 2	Data			
1	**1**	**2**	S_{11}	S_{21}	S_{12}	S_{22}
2	**1**	**3**	▨	S_{31}	S_{13}	S_{33}
3	**1**	**4**	▨	S_{41}	S_{14}	S_{44}
4	**2**	**3**	▨	S_{32}	S_{23}	▨
5	**2**	**4**	▨	S_{42}	S_{24}	▨
6	**3**	**4**	▨	S_{43}	S_{34}	▨

Table 4. Test sequence to completely characterize a 3-way splitter.

7.7 The following table lists the correlation between s-parameter data and RF measurements. Since the splitter response is essentially the same in both forward and reverse directions, some of the s-parameters are redundant for report purposes.

All of the cells in this matrix are necessary to assemble a complete s-parameter file that can be used for circuit simulation.

S_{11} R/L in	S_{21} IL in--2	S_{31} IL in--3	S_{41} IL in--4
S_{12} IL 2--in	S_{22} R/L 2	S_{32} ISO 2--3	S_{42} ISO 2--4
S_{13} IL 3--in	S_{23} ISO 3--2	S_{33} R/L 3	S_{43} ISO 3--4
S_{14} IL 4--in	S_{24} ISO 4--2	S_{34} ISO 4--3	S_{44} R/L 4

Table5. Matrix of all the 4-port S-parameters and the corresponding splitter measurements.

7.8 The previous examples of data collection can be expanded as the number of ports increases. This indicates an increasing dependence on software and automation.

8.0 APPENDIX 2 TEST METHOD FOR DIRECTIONAL COUPLERS

8.1 Recall the instrument state defined in section 4 (setup). Verify that the frequency range, power level and display properties are suitable to the device.

8.1.1 If the display properties are changed, the new state can be saved in another memory register without recalibration.

8.1.2 If the frequency range or power levels are changed, recalibration is recommended to maintain error correction accuracy.

8.1.3 If the cables or adapters are changed, recalibration is necessary.

8.2 Define a numbering system for the ports of the directional coupler beginning with the input as port 1. In this example, port 2 will be the thru port, and port 3 will be the tap port.

8.3 Follow the test procedure defined above in section 5.3 for two-port transmission.

8.4 The following table lists the order of tests and cable connections required to make a complete set of s-parameters for a 3-port directional coupler. The bold numbers are the coupler ports. It shows how nine data sets are derived from three tests.

Test #	NA port 1	NA port 2	Data			
1	1	2	S_{11}	S_{21}	S_{12}	S_{22}
2	1	3		S_{31}	S_{13}	S_{33}
3	2	3		S_{32}	S_{23}	

Table 6. Test sequence to completely characterize a directional coupler.

8.5 **THE FOLLOWING TABLE LISTS THE CORRELATION BETWEEN S-PARAMETERS AND RF MEASUREMENTS. SINCE THE COUPLER RESPONSE IS ESSENTIALLY THE SAME IN BOTH FORWARD AND REVERSE DIRECTIONS, SOME OF THE S-PARAMETERS ARE REDUNDANT FOR REPORT PURPOSES.**

R/L means Return Loss

IL means Insertion Loss

ISO means Isolation

Each cell in the matrix represents a 801-point data set of magnitude and angle vs. frequency.

S_{11} R/L in	S_{21} IL thru	S_{31} IL tap
S_{12} IL 2--in	S_{22} R/L thru	S_{32} ISO 2--3
S_{13} IL 3--in	S_{23} ISO 3--2	S_{33} R/L tap

Table 7. Matrix of all the 3-port S-parameters and corresponding coupler measurements.