APPLICATION NOTE

10 Hints for Making Better Network Analyzer Measurements

Introduction

This application note contains a variety of hints to help you understand and improve your use of network analyzers, along with a quick summary of network analyzers and their capabilities.

Overview of network analyzers

Network analyzers characterize active and passive components, such as amplifiers, mixers, duplexers, filters, couplers, and attenuators. These components are used in systems as common and low-cost as pagers, or in systems as complex and expensive as communications or radar systems. Components can have one port (input or output) or many ports. The ability to measure the input characteristics of each port, as well as the transfer characteristics from one port to another, gives designers the knowledge to configure a component as part of a larger system.



KEYSIGHT TECHNOLOGIES

Types of network analyzers

Vector network analyzers (VNAs) are the most powerful kind of network analyzer and can measure frequencies from 5 Hz up to 120 GHz. Designers and final test in manufacturing use VNAs because they measure and display the complete amplitude and phase characteristics of an electrical network. These characteristics include S-parameters, magnitude and phase, standing wave ratios (SWR), insertion loss or gain, attenuation, group delay, return loss, reflection coefficient, and gain compression VNA hardware consists of a sweeping signal source (usually internal), a test set to separate forward and reverse test signals, and a multichannel, phase-coherent, highly sensitive receiver (Figure 1). In the RF and microwave bands, typical measured parameters are referred to as S-parameters, and are also commonly used in computer-aided design models.

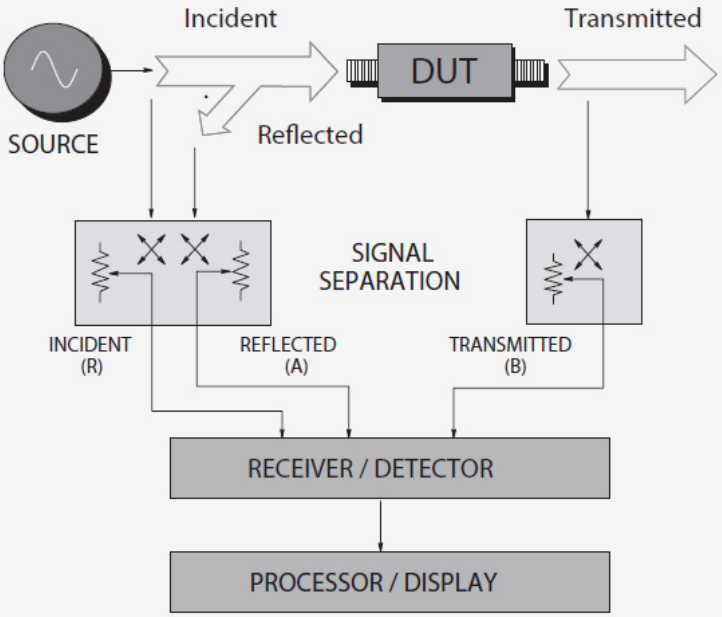


Figure 1. Network analyzer block diagram

Scalar network analyzers

A scalar network analyzer (SNA) measures only the amplitude portion of the S-parameters, resulting in measurements such as transmission gain and loss, return loss, and SWR. Once a passive or active component has been designed using the total measurement capability of a VNA, an SNA may be a more cost-effective measurement tool for the production line to reveal out-of-specification components. While SNAs require an external or internal sweeping signal source and signal separation hardware, they only need simple amplitude-only detectors, rather than complex (and more expensive) phase-coherent detectors.

Network/spectrum analyzers

A network/spectrum analyzer eliminates the circuit duplication in a bench test setup of a network and spectrum analyzer. Frequency coverage ranges from 10 Hz to 1.8 GHz. These combination instruments can be economical alternatives in design and test of active components like amplifiers and mixers, where analysis of signal performance is also needed.

Hint 1. How to boost and attenuate signal levels when measuring high-power amplifiers

Testing high-power amplifiers can sometimes be challenging since the signal levels needed for test may be beyond the stimulus/response range of the network analyzer. High-power amplifiers often require high input levels to characterize them under conditions similar to actual operation. Often these realistic operating conditions also mean the output power of the amplifier exceeds the compression or burn-out level of the analyzer's receiver.

When you need an input level higher than the network analyzer's source can provide, a preamplifier can be used to boost the power level prior to the amplifier under test (AUT). By using a coupler on the output of the preamplifier, a portion of the boosted input signal can be used for the analyzer's reference channel (Figure 2). This configuration removes the preamplifier's frequency response and drift errors (by ratioing), which yields an accurate measurement of the AUT alone.

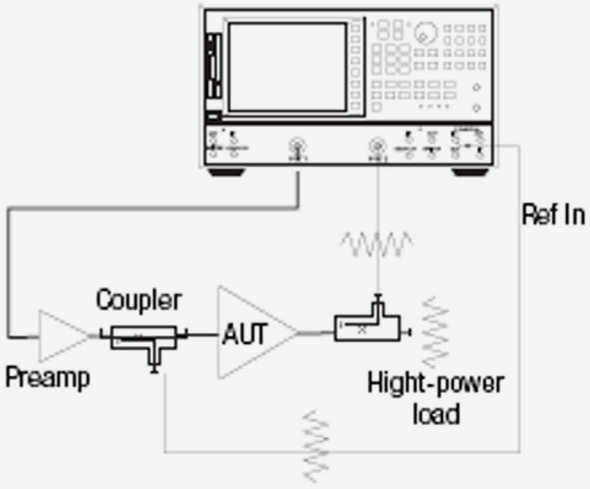


Figure 2. High-powered forward measurement configuration

When the output power of the AUT exceeds the input compression level of the analyzer's receiver, some type of attenuation is needed to reduce the output level. This can be accomplished by using couplers, attenuators, or a combination of both. Care must be taken to choose components that can absorb the high power from the AUT without sustaining damage. Most loads designed for small-signal use can only handle up to about one watt of power. Beyond that, special loads that can dissipate more power must be used.

The frequency-response effects of the attenuators and couplers can be removed or minimized by using the appropriate type of error-correction. One concern when calibrating with extra attenuation is that the input levels to the receiver may be low during the calibration cycle. The power levels must be significantly above the noise floor of the receiver for accurate measurements. For this reason, network analyzers that have narrowband, tuned receivers are typically used for high-power applications since their noise floor is typically 90 dBm, and they exhibit excellent receiver linearity over a wide range of power levels.

Some network analyzers with full two-port S-parameter capability enable measuring of the reverse characteristics of the AUT to allow full two-port error correction. In this configuration, the preamplifier must be added in the signal path before the port 1 coupler (Figure 3). Otherwise, the preamplifier's reverse isolation will prevent accurate measurements from being made on port 1. If attenuation is added to the output port of the analyzer, it is best to use a higher power in the reverse direction to reduce noise effects in the measurement of S22 and S12. Many VNAs allow uncoupling of the test-port power to accommodate different levels in the forward and reverse directions.

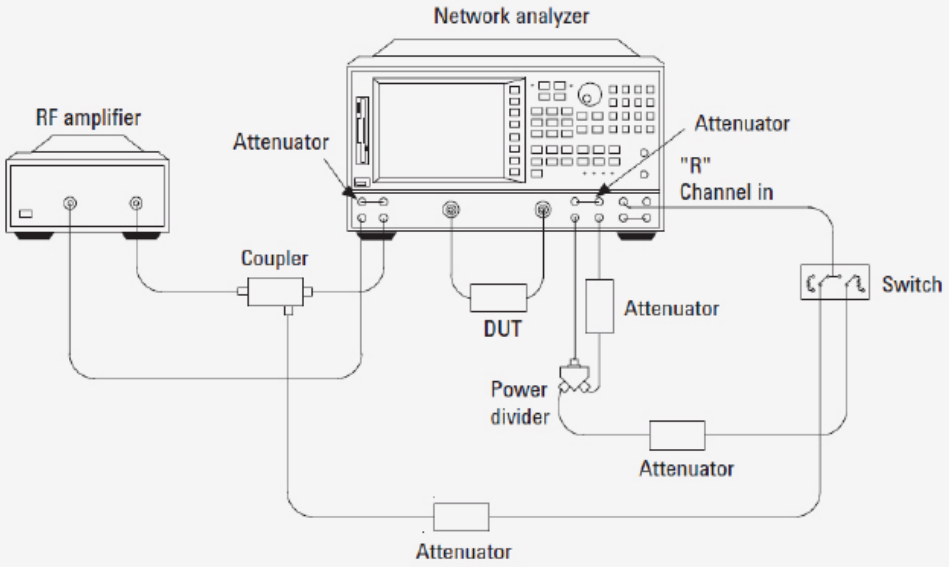


Figure 3. High-powered forward and reverse measurement configuration

Hint 2. Compensate for time delay for better cable measurements

A network analyzer sweeps its source frequency and tuned receiver at the same time to make stimulus/response measurements. Since the frequency of a signal coming from a device under test (DUT) may not be exactly the same as the network analyzer frequency at a given instant of time, this can sometimes lead to confusing measurement results. If the DUT is a long cable with time delay T and the network analyzer sweep rate is df/dt, the signal frequency at the end of the cable (input to the vector network analyzer's receiver) will lag behind the network analyzer source frequency by the amount F=T*df/dt. If this frequency shift is appreciable compared to the network analyzer's IF detection bandwidth (typically a few kHz), then the measured result will be in error by the rolloff of the IF filter.

Figure 4 shows this effect when measuring the transmission response of a 12-foot cable on an 8714ET network analyzer. The upper trace shows the true response of the cable, using a 1-second sweep time. The lower trace uses the default sweep time of 129 msec, and the data is in error by about –0.5 dB due to the frequency shift through the cable. This sweep time is too fast for this particular DUT.

The lower trace of Figure 5 shows an even more confusing result when measuring the same cable on an 8753ES with 100-msec sweep time. Not only is there an error in the data, but the size of the error makes some sharp jumps at certain frequencies. These frequencies are the band-edge frequencies in the 8753ES, and the trace jumps because the network analyzer's sweep rate (df/dt) changes in different bands. This leads to a different frequency shift through the cable, and hence, a different amount of error in the data. In this case, instead of increasing the sweep time, the situation can be corrected by removing the R channel jumper on the front panel of the 8753ES and connecting a second cable of about the same length as the DUT cable. This balances the delays in the reference and test paths, so that the network analyzer's ratioed transmission measurement does not have the frequency-shift error. The upper trace of Figure 5 shows a measurement of the DUT using the same 100-msec sweep time, but with the matching cable in R channel.

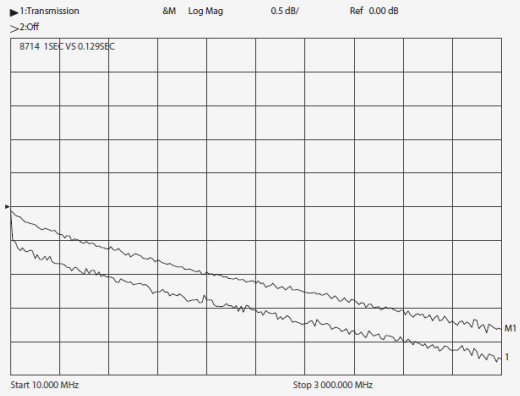


Figure 4. Reduce measurement error by increasing swap time

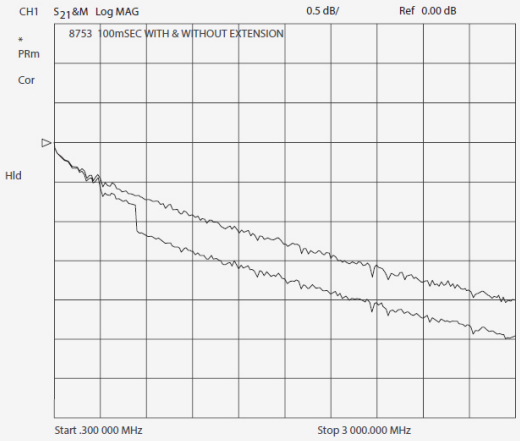


Figure 5. Reduce measurement error by balancing reference path

Hint 3. Proper termination — Key to improving reflection measurements

Making accurate reflection measurements on two-port devices with transmission/reflection (T/R)-based analyzers (such as the 8712ET and 8714ET RF analyzers) requires a good termination on the unmeasured port. This is especially true for low-loss, bidirectional devices such as filter passbands and cables. T/R based analyzers only offer one-port calibration for reflection measurements, which corrects for errors caused by directivity, source match and frequency response, but not load match.

One-port calibration assumes a good termination at port 2 of the device under test (the port not being measured), since load match is not corrected. One way to achieve this is by connecting a high quality load (a load from a calibration kit, for example) to port 2 of the device. This technique yields measurement accuracy on a par with more expensive S-parameter based analyzers that use full two-port calibration.

However, if port 2 of the device is connected directly to the network analyzer's test port, the assumption of a good load termination is not valid. In this case, measurement accuracy can be improved considerably by placing an attenuator (6 to 10 dB, for example) between port 2 of the device and the test port of the analyzer. This improves the effective load match of the analyzer by twice the value of the attenuator.

Figure 6 shows an example of how this works. Let's say we are measuring a filter with 1 dB of insertion loss and 16 dB of return loss (Figure 6A). Using an analyzer with an 18 dB load match and 40 dB directivity would yield a worst-case measurement uncertainty for return loss of –4.6 dB, +10.4 dB. This is a rather large variation that might cause a filter that didn't meet its specifications to pass, or a good filter to fail. Figure 6B shows how adding a high-quality (for example, VSWR = 1.05, or 32 dB match) 10-dB attenuator improves the load match of the analyzer to 29 dB [(2 x 10 + 18 dB) combined with 32 dB]. Now our worst-case measurement uncertainty is reduced to +2.5 dB, –1.9 dB, which is much more reasonable.

An example where one-port calibration can be used quite effectively without any series attenuation is when measuring the input match of amplifiers with high-reverse isolation. In this case, the amplifier's isolation essentially eliminates the effect of imperfect load match.

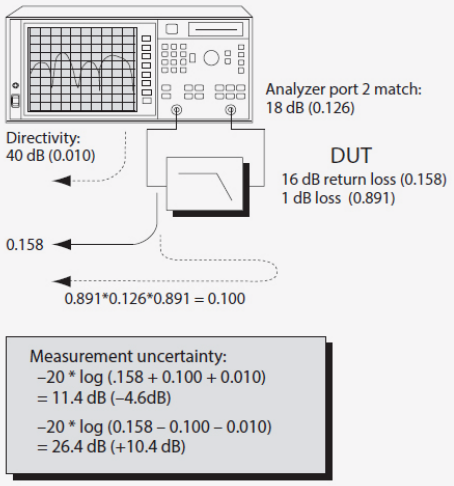


Figure 6A. Reflection measurement uncertainty

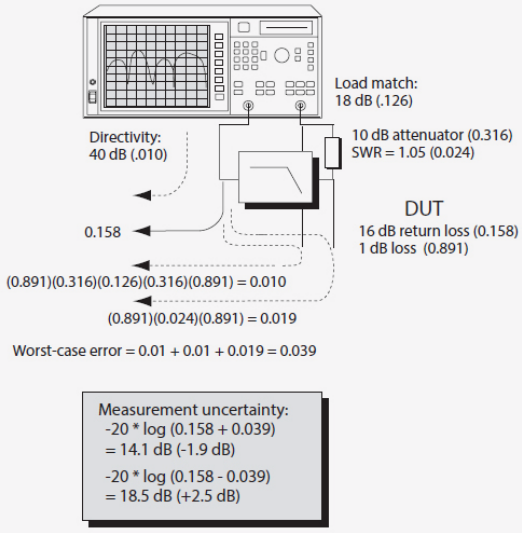


Figure 6B. Measurement uncertainty improvement

Hint 4. Use frequency-offset mode for accurate measurements of mixers, converters and tuners

Frequency-translating devices such as mixers, tuners, and converters present unique measurement challenges since their input and output frequencies differ. The traditional way to measure these devices is with broadband diode detection. This technique allows scalar measurments only, with medium dynamic range and moderate measurement accuracy.

For higher accuracy, vector network analyzers such as the 8753ES and 8720ES offer a frequency-offset mode where the frequency of the internal RF source can be arbitrarily offset from the analyzer's receivers. Narrowband detection can be used with this mode, providing high dynamic range and good measurement accuracy, as well as the ability to measure phase and group delay.

There are two basic ways that frequency offset mode can be used. The simplest way is to take the output from the mixer or tuner directly into the reference input on the analyzer (Figure 7A). This technique offers scalar measurements only, with up to 35 dB of dynamic range; beyond that, the analyzer's source will not phase lock properly. For mixers, an external LO must be provided. After specifying the measurement setup from the front panel, the proper RF frequency span is calculated by the analyzer to produce the desired IF frequencies, which the receiver will tune to during the sweep. The network analyzer will even sweep the RF source backward if necessary to provide the specified IF span.

For high-dynamic-range amplitude measurements, a reference mixer must be used (Figure 7B). This mixer provides a signal to the R channel for proper phase lock, but does not affect measurements of the DUT since it is not in the measurement path. For phase or delay measurements, a reference mixer must also be used. The reference mixer and the DUT must share a common LO to guarantee phase coherency.

When testing mixers, either technique requires an IF filter to remove the mixer's undesired mixing products as well as the RF and LO leakage signals.

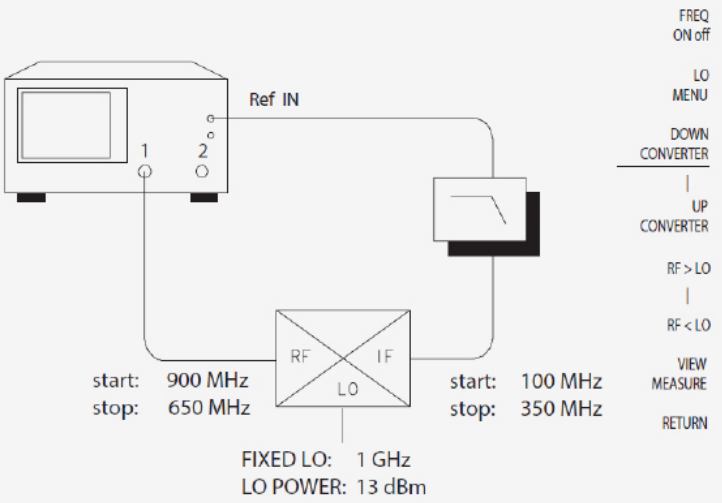


Figure 7A. Mixer measurement setup

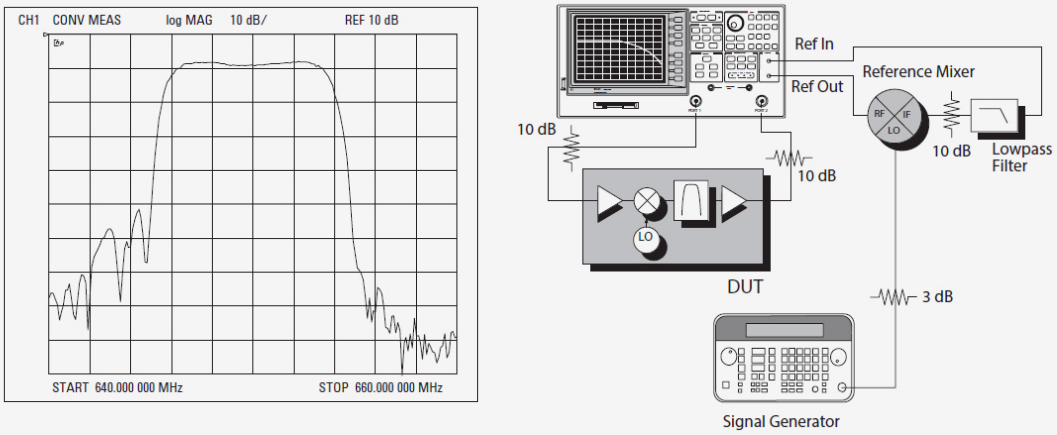


Figure 7B. High dynamic range conversion loss measurement (left) and high dynamic range setup (right)

Hint 5. Increasing the accuracy of noninsertible device measurements

Full two-port error correction provides the best accuracy when measuring RF and microwave components. But if you have a noninsertible device (for example, one with female connectors on both ports), then its test ports cannot be directly connected during calibration. Extra care is needed when making this through connection, especially while measuring a device that has poor output match, such as an amplifier or a low-loss device.

There are five basic ways to handle the potential errors with a through connection for a noninsertible device:

1. **Use electronic calibration (ECal) modules.**

This is the simplest and fastest non-insertible calibration method in existence. This method uses an ECal module with the same connectors that match the device under test. Full two-port error correction, defined at the test ports, is achievable. All Keysight Technologies, Inc. ECal modules are characterized at the factory and provide a traceable calibration path.

2. **Use a very short through.**

This allows you to disregard the potential errors. When you connect port 1 to port 2 during a calibration, the analyzer calculates the return loss of the second port (the load match) as well as the transmission term. When the calibration kit definition does not contain the correct length of the through, an error occurs in the measurement of the load match. If a barrel is used to connect port 1 to port 2, the measurement of the port 2 match will not have the correct phase, and the error-correction algorithm will not remove the effects of an imperfect port 2 impedance.

This approach will work well enough if the through connection is quite short. However, for a typical network analyzer, “short” means less than one-hundredth of a wavelength. If the through connection is one-tenth of a wavelength (at the frequency of interest), the corrected load match is no better than the raw load match. As the through length approaches a one-quarter wavelength, the residual load match can actually get as high as 6 dB worse than the raw load match. For a 1-GHz measurement, one-hundredth of a wavelength means less than 3 mm (about 0.12 inches).

3. **Use swap-equal-adapters.**

In this method you use two matched adapters of the same electrical length, one with male/female connectors and one that matches the device under test.

Suppose your instrument test ports are both male, such as the ends of a pair of test-port cables, and your device has two female ports. Put a female-to-female through adapter, usually on port 2, and do the transmission portion of the calibration. After the four transmission measurements, swap in the male-to-female adapter (now you have two male test ports), and do the reflection portion of the calibration (Figure 8). Now you are ready to measure your device. All the adapters in the calibration kits are of equal electrical length (even if their physical lengths are different).

4. **Modify the through-line standard.**

If your application is manufacturing test, the “swap-equaladapters” method’s requirement for additional adapters may be a drawback. Instead, it is possible to modify the calibration kit definition to include the length of the through line. If the calibration kit has been modified to take into account the loss and delay of the through, then the correct value for load match will be measured. It’s easy to find these values for the male-to-male through and the female-to-female through. First, do a swap-equal-adapter calibration, ending up with both female or both male test ports. Then simply measure the “noninsertible” through and look at S21 delay (use the midband value) and loss at 1 GHz. Use this value to modify the calibration kit.

5. **Use the adapter-removal technique.**

Many Keysight vector network analyzer models offer an adapter-removal technique to eliminate all effects of through adapters. This technique yields the most accurate measurement results, but requires two full two-port calibrations.

Non-insertible device

1. Transmission cal using adapter A.
2. Reection cal using adapter B. Length of adapters must be equal.
3. Measure DUT using adapter B.

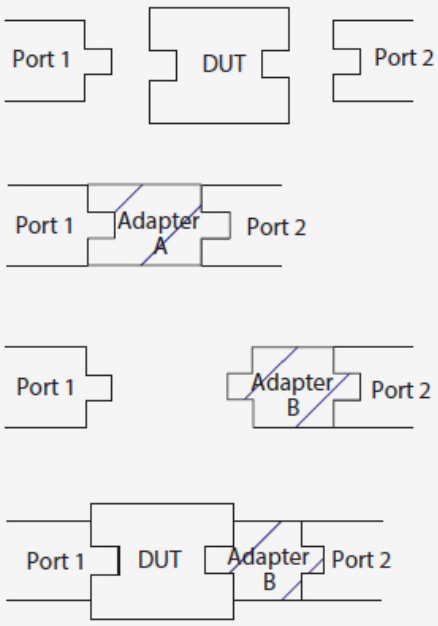


Figure 8. Swap-equal-adapters method

Hint 6. Check for aliasing in phase or delay format

When measuring a device under test (DUT) that has a long electrical length, use care to select appropriate measurement parameters. The VNA samples its data at discrete frequency points, then “connects the dots” on the display to make it more visually appealing. If the phase shift of the DUT changes by more than 180 degrees between adjacent frequency points, the display can look like the phase slope is reversed! The data is undersampled and aliasing occurs. This is analogous to filming a wagon wheel in motion, where typically too few frames are shot to accurately portray the motion and the wheel appears to spin backward.

In addition, the VNA calculates group delay data from phase data. If the slope of the phase is reversed, then the group delay will change sign. A surface acoustic wave (SAW) filter may appear to have negative group delay—clearly not a correct answer. If you suspect aliasing in your measurements, try this simple test. Just decrease the spacing between frequency points and see if the data on the VNA’s display changes.Either increase the number of points, or reduce the frequency span.

Figure 9 shows a measurement of a SAW bandpass filter on an 8714ET RF economy network analyzer, with 51 points in the display. The indicated group delay is negative— a physical impossibility. But if the number of points increases to 201 (Figure 10), it becomes clear that the VNA settings created an aliasing problem.

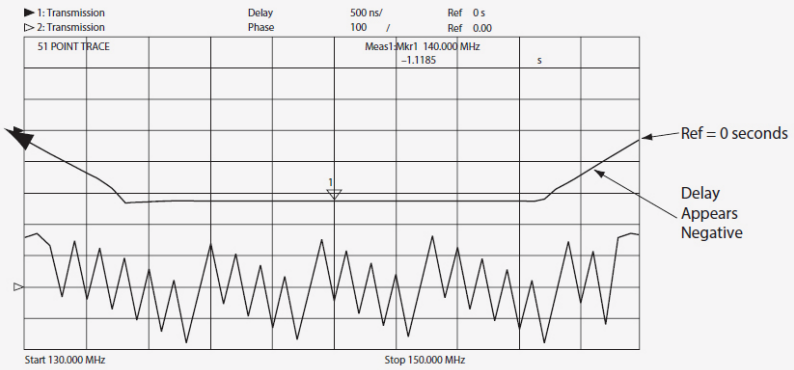


Figure 9. Filter measurement with insufficient number of points

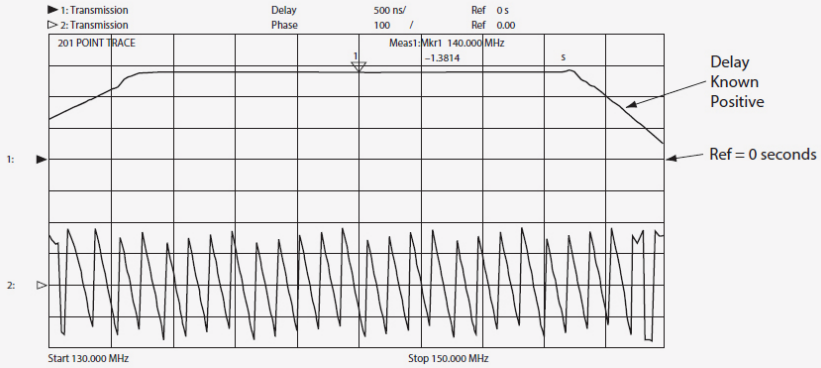


Figure 10. Filter measurement with correct number of points

Hint 7. Quick calibration verification

If you've ever measured a device and the measurements didn't look quite right, or you were unsure about a particular analyzer's accuracy or performance, here are a few "quick check" methods you can use to verify an instrument's calibration or performance. All you need are a few calibration standards.

Verifying reflection measurements

To verify reflection (S11) measurements on the source port (port 1), perform one or more of the following steps:

1. For a quick first check, leave port 1 open and verify that the magnitude of S11 is near 0 dB (within about ±1 dB).
2. Connect a load calibration standard to port 1. The magnitude of S11 should be less than the specified calibrated directivity of the analyzer (typically less than –30 dB) (Figure 11).
3. Connect either an open or short circuit calibration standard to port 1. The magnitude of S11 should be close to 0 dB (within a few tenths of a dB).

To verify transmission (S21) measurements:

1. Connect a through cable from port 1 to port 2. The magnitude of S21 should be close to 0 dB (within a few tenths of a dB).
2. To verify S21 isolation, connect two loads: one on port 1 and one on port 2. Measure the magnitude of S21 and verify that it is less than the specified isolation (typically less than –80 dB).

To get a more accurate range of expected values for these measurements, consult the analyzer's specifications. You might also consider doing these verifications immediately after a calibration to verify the quality of the calibration. To ensure that you are performing a calibration verification, and not a connection repeatability test, be sure to use a set of standards that are different than those used as part of the calibration process.

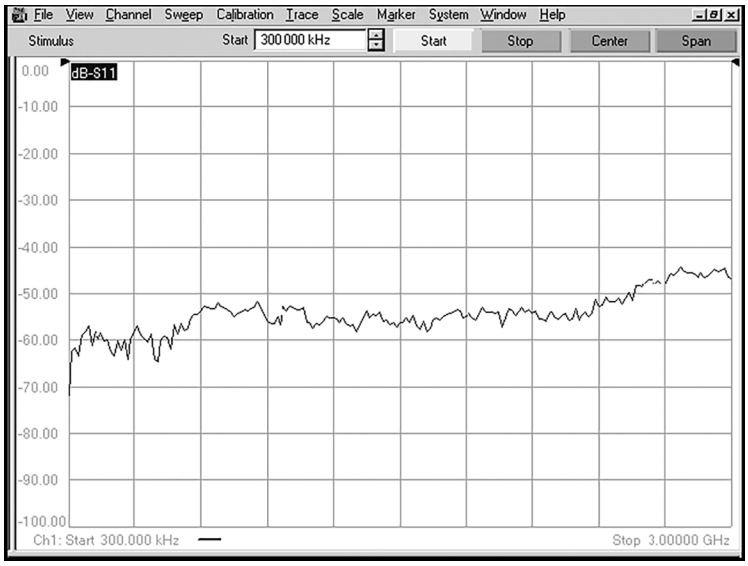


Figure 11. Measurement of load standard after calibration

Hint 8. Making your measurements real-time, accurate and automated

Tuning and testing RF devices in a production environment often requires speed and accuracy from a network analyzer. However, at fast sweep speeds an analyzer's optimum accuracy may be unavailable.

Using a segmented sweep

Many network analyzers have the ability to define a sweep consisting of several individual segments. Each segment can have its own stop and start frequency, number of data points, IF bandwidth, and power level. Using a segmented sweep, the measurement can be optimized for speed and dynamic range (Figure 12).

Data resolution can be made high where needed (more data points) and low where not needed (less data points); frequency ranges can be skipped where data is not needed at all; the IF bandwidth can be large when high dynamic range is not necessary, which decreases the sweep time, and small when high dynamic range is required; the power level can be decreased in the passband and increased in the stopband for devices that contain a filter followed by an amplifier (for example, a cellulartelephone basestation receiver filter/LNA combination).

Instrument automation

For more complex testing such as final test, an analyzer with IBASIC (8712/8714, E5100), or Microsoft VBA (ENA) programming capability provides complex computation and control so you can easily automate measurements.

Using the program doesn't require programming experience. You can easily customize each test or combination of tests and activate them by a softkey or footswitch to automatically set up system parameters for each device you test.

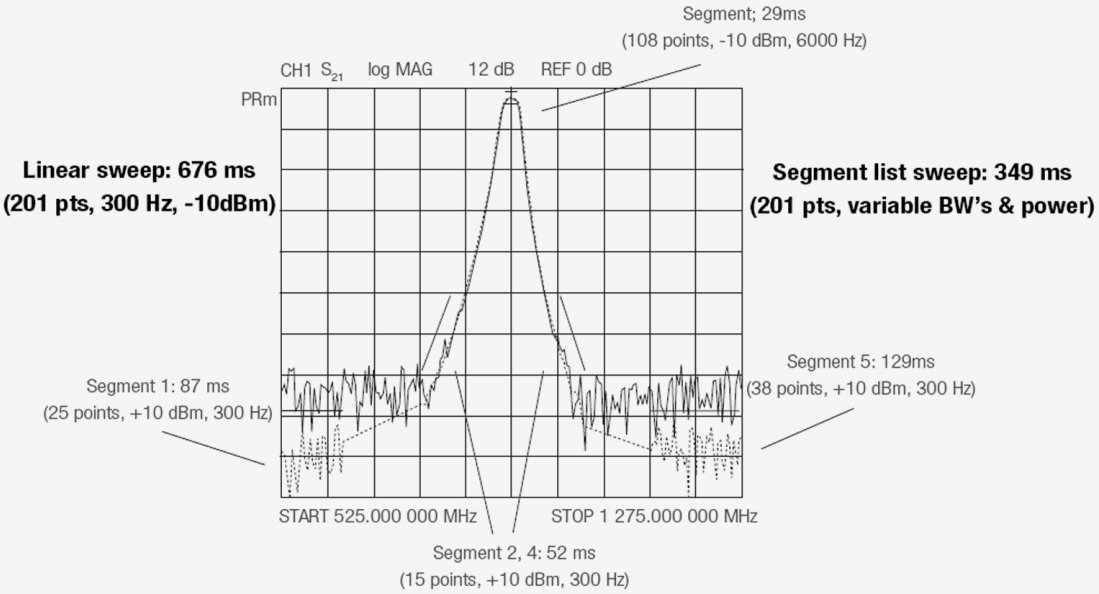


Figure 12. Optimize filter measurements with segment list mode

Hint 9. Making high dynamic range measurements

Extend the dynamic range measurement capability of your network analyzer by bypassing the coupler at test port 2 (for forward transmission measurements). Since the coupler is no longer in the measurement path, the associated loss through the coupled arm no longer impacts the measurement. This increases the effective sensitivity of the analyzer. Since the coupler is no longer part of the signal path, it is no longer possible to make reverse measurements.

To take advantage of this increased sensitivity, the power level into the receiver must be monitored to prevent compression. For devices such as filters, this is easily done using a segmented sweep, where the power is set high in the stopbands (+10 dBm typically), and low in the passband (-6 dBm typically).

Maintain full S-parameter error correction

Depending on the particular network analyzer configuration, it is possible to configure a signal path that maintains usage of the port 2 coupler, but simply reverses the direction of signal travel (Figure 13). By reversing the port 2 coupler, the transmitted signal travels to the “B” receiver via the main arm of the coupler, instead of the coupled arm. Reverse dynamic range measurements will be lower because the stimulus signal must now travel via the coupled arm. Since both forward and reverse measurements are possible, it is still possible to apply full twoport error correction.

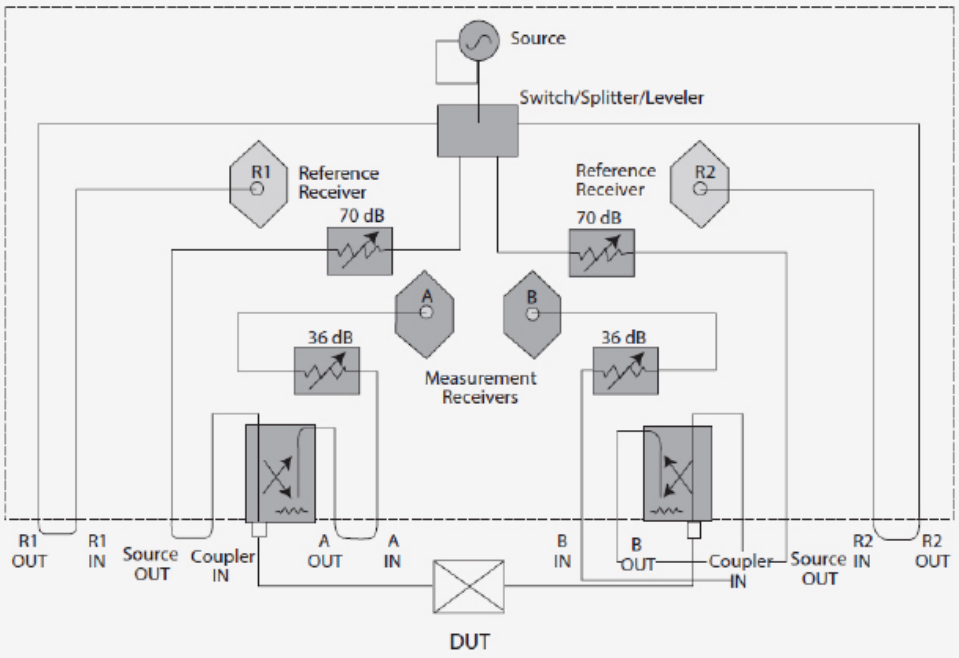


Figure 13. High dynamic range configuration that allows both forward and reverse measurements

Hint 10. Simplifying multiport measurements

High-volume tuning and testing of multiport devices (devices with more than two ports)can be greatly simplified by using a multiport network analyzer, or a multiport test set with a traditional two-port analyzer.

A single connection to each port of the device under test (DUT) allows for complete testing of all transmission paths and port reflection characteristics. Multiport test systems eliminate time-consuming reconnections to the DUT, keeping production costs down and throughput up. By reducing the number of RF connections, the risk of misconnections is lowered, operator fatigue is reduced, and the wear on cables, fixtures, connectors, and the DUT is minimized.

Measuring balanced devices

While ideal balanced components only respond to or produce differential (out-of-phase) signals, realworld devices also respond to or produce common-mode (in-phase) signals. Newer analyzers (such as Keysight's ENA Series and PNA Series) provide built-in firmware (Figure 14) and/or software packages that performs a series of single-ended stimulus/ response measurements on all measurement paths of the DUT, and then calculates and displays the differential mode, common-mode, and mode conversion S-parameters.

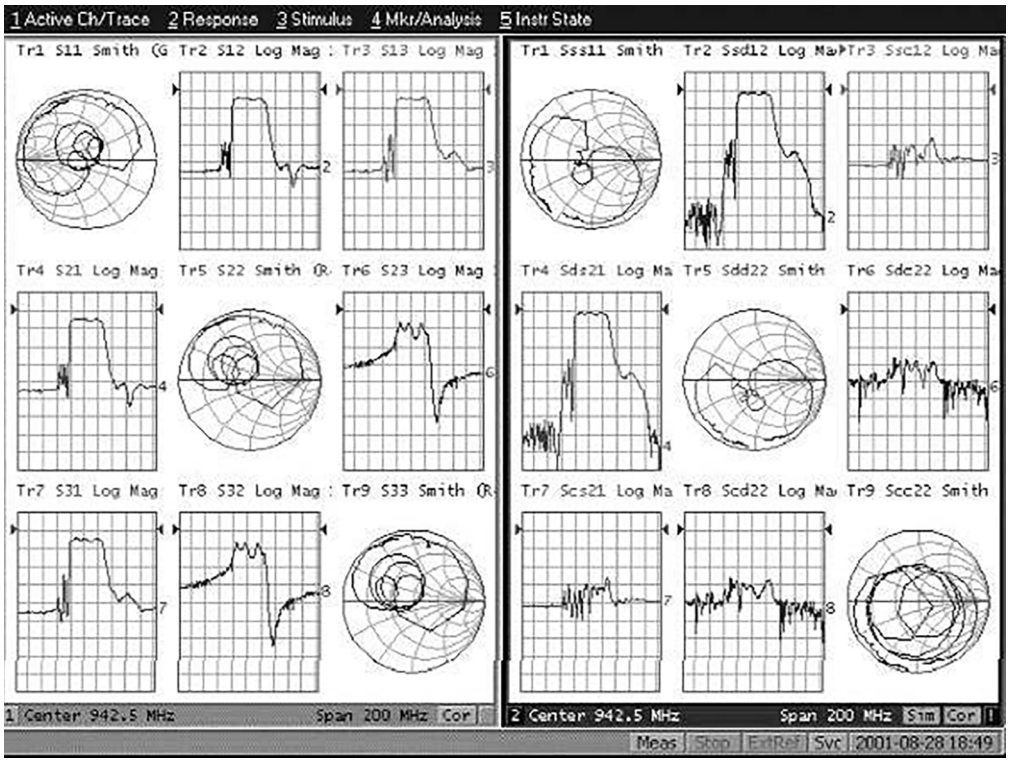


Figure 14. Single-ended and corresponding mixed-mode measurement parameters

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