

Improve Your Network Analyzer Measurements

Operating a network analyzer is not always a straightforward task.

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Network analyzers are vital tools for helping you characterize active and passive components such as amplifiers, mixers, duplexers, filters, couplers, and attenuators. These components are used in systems as common and inexpensive as pagers, and in systems as complex and expensive as radar systems. They can have anywhere from one input or output port to many ports. The ability to measure the input characteristics of each port and the transfer characteristics from one port to another gives you the information required to configure a component as part of a larger system. Figure 1 is a block diagram of a typical network analyzer.

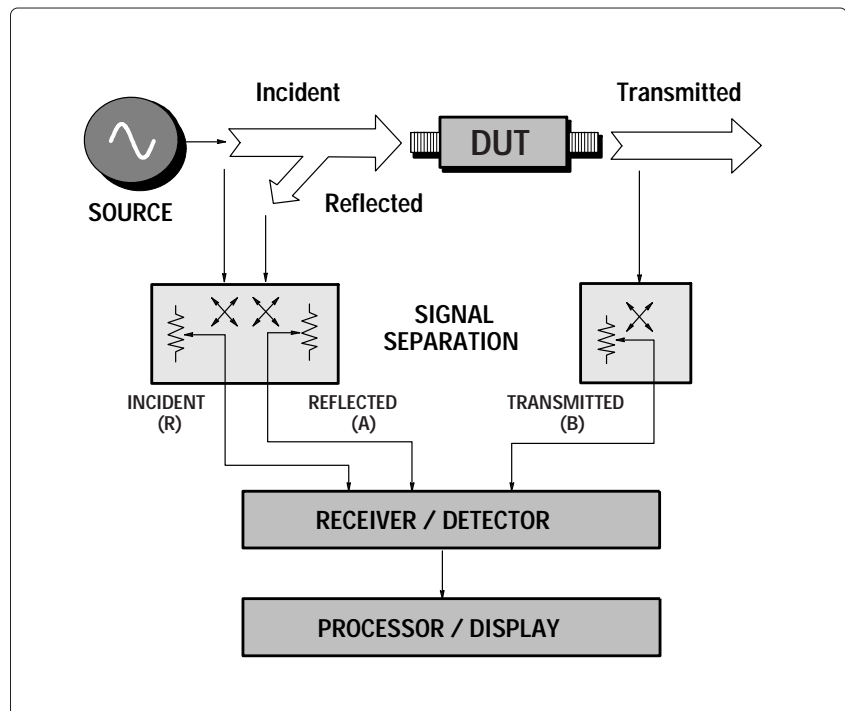


Figure 1. Network analyzer block diagram

Types of Network Analyzers

A vector network analyzer (VNA) is the most powerful kind of network analyzer. It is used for design verification and final test in manufacturing when the complete amplitude and phase characteristics of an electrical network must be displayed. These characteristics include S-parameters, magnitude and phase, standing wave ratios (SWRs), insertion loss or gain, attenuation, group delay, return loss, reflection coefficient, and gain compression. VNAs can measure frequencies from 5 Hz to 110 GHz. 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.

A scalar network analyzer (SNA) measures only the amplitude portion of the S-parameters, and so obtains measurements such as transmission gain and loss, return loss, and SWR. After a passive or active component has been designed using the more extensive measurement capability of a VNA, an SNA may be a more cost-effective measurement tool for revealing out-of-specification

components on the production line. Like VNAs, SNAs require an external or internal sweeping signal source and signal-separation hardware, but they just need simple amplitude-only detectors, rather than complex (and more expensive) phase-coherent detectors.

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

Using a network analyzer is not always a straightforward task. The following techniques can help you improve the speed and accuracy of network analyzer measurements.

Boosting and Attenuating Signal Levels When Measuring High-Power Amplifiers

Testing high-power amplifiers can be challenging when the signal levels needed for test are beyond the stimulus/response range of the network analyzer. High-power amplifiers often require high input levels for characterization under condi-

tions similar to actual operation. However, these realistic operating conditions also cause the output power of the amplifier to exceed the compression or burn-out level of the analyzer's receiver.

When the amplifier under test (AUT) needs an input level higher than the network analyzer's source can provide, you can put a preamplifier in front of the AUT to boost the power level. If you add 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), yielding an accurate measurement of the AUT alone.

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 with couplers, attenuators, or a combination of both. You must choose components that can absorb the high power from the AUT without sustaining damage, as most loads designed for small-signal use can only handle up to about one watt of power.

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. Therefore, network analyzers that have narrowband, tuned receivers are typically used for high-power applications because their noise floor is typically less than or equal to -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 allow measuring the reverse characteristics of the AUT, allowing 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

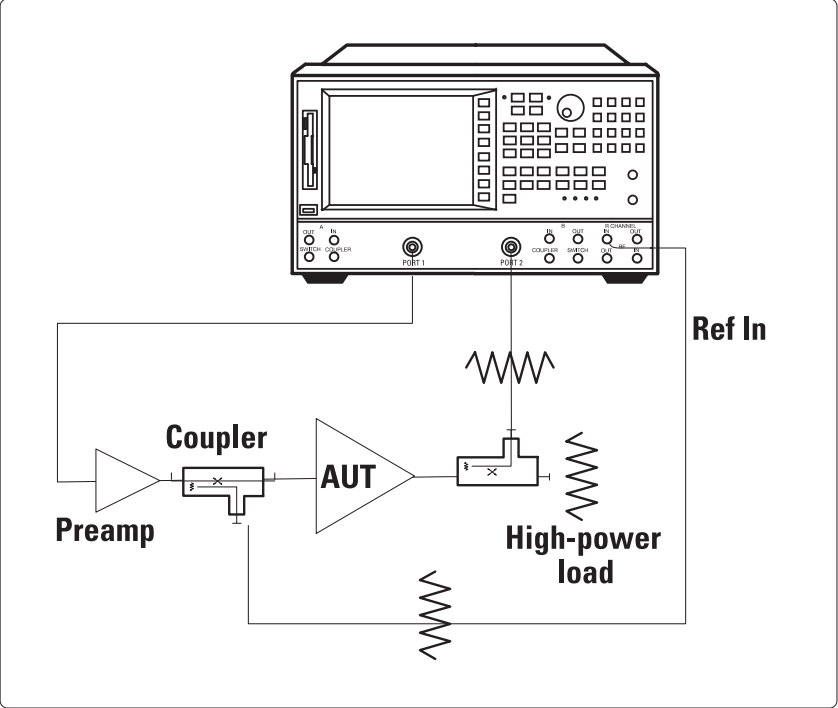


Figure 2. Interfacing a network analyzer to an amplifier that requires an input level higher than the network analyzer's source can provide

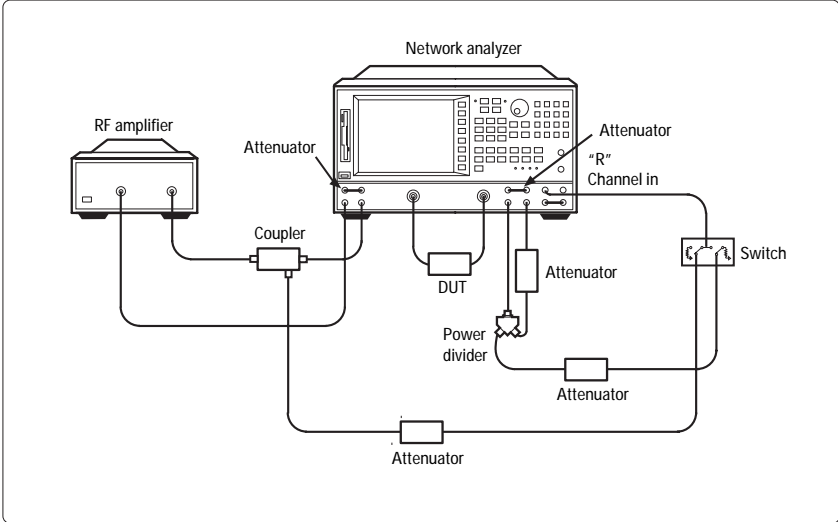


Figure 3. Connections to high-level signals that allow full two-port error correction

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.

Compensating for Time Delay for More-Accurate Cable Measurements

A network analyzer sweeps its source frequency and tuned receiver at the same time to make stimulus-response measurements. Because 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, this can 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 significant compared to the network analyzer's IF detection bandwidth (typically a few kilohertz), then the measured result will be in error by the rolloff of the IF filter.

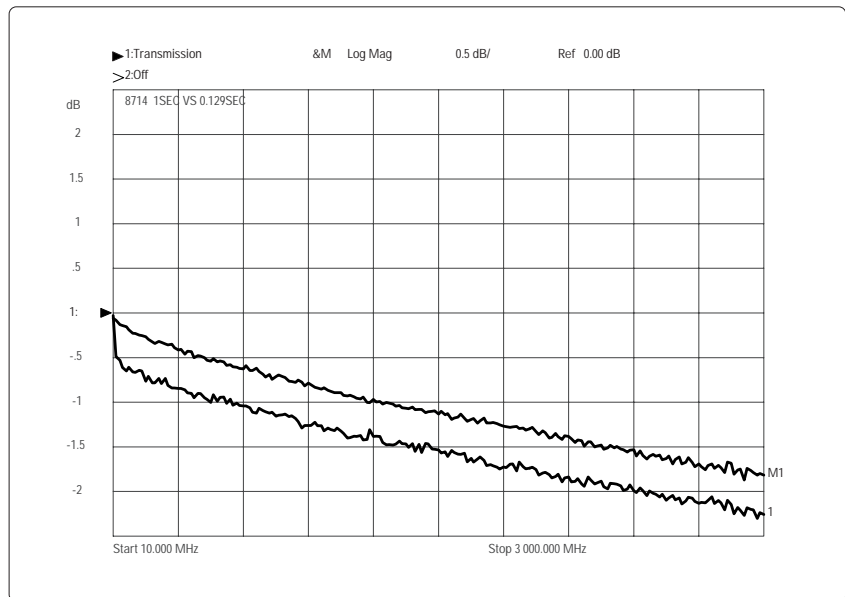


Figure 4a. Erroneous transmission response of a 12-foot cable (lower trace) compared to the true response (upper trace).

Figure 4a shows this effect when measuring the transmission response of a 12-foot cable on a 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 ms, 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 result is even more confusing when measuring the same cable using a different network analyzer with a 100-ms sweep time. Not only is there an error in the data, but the size of the error makes some sharp jumps

at certain frequencies (lower trace of figure 4b). These frequencies are the band-edge frequencies in the network analyzer, and the trace jumps because its sweep rate (df/dt) changes in different bands. This leads to a varying frequency shift through the cable, and hence a varying 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 network analyzer 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 measure-

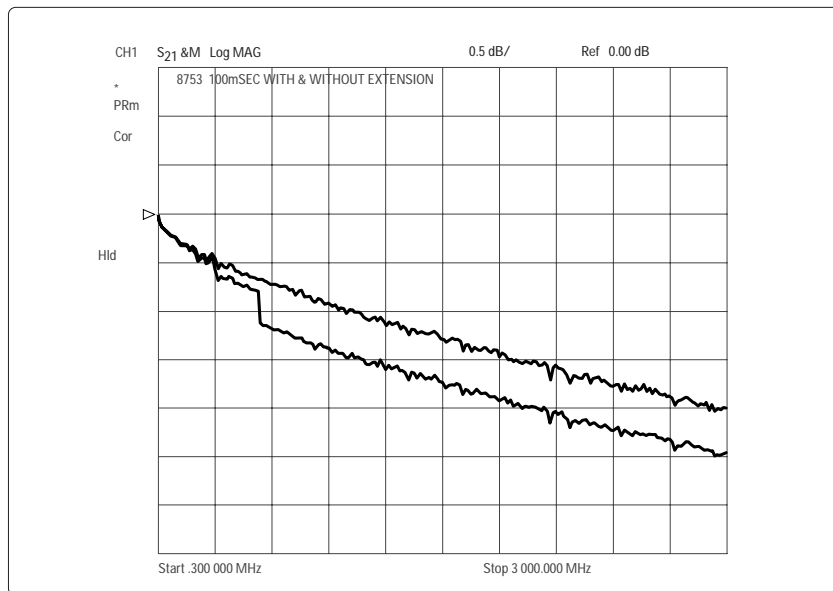


Figure 4b. Measured data can jump as the sweep rate changes in different bands.

ment does not have the frequency-shift error. The upper trace of figure 4b shows a measurement of the DUT using the same 100-ms sweep time, but with the matching cable in R channel.

Terminating the Unmeasured Port for Accurate Reflection Measurements with Two-Port Devices

Making accurate reflection measurements on two-port devices using a transmission/reflection (T/R)-based analyzer requires a good termination on the unmeasured port. This is particularly important for low-loss, bidirectional devices such as filter

passbands and cables. T/R-based analyzers offer only 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 DUT (the port not being measured), as load match is not corrected. One way to achieve this is by connecting a high-quality load (such as a load from a calibration kit) to port 2 of the device. This technique yields measurement accuracy on 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, you cannot assume a good load termination. 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 5 shows an example of how this works. When measuring a filter with 1 dB of insertion loss and 16 dB of return loss, 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 (figure 5a). This is a large variation that might cause a filter that didn't meet its specifications to pass, or a good filter to fail. Figure 5b shows how adding a high-quality 10-dB attenuator (for example, VSWR = 1.05, or 32-dB match) improves the load match of the analyzer to 29 dB ((2x 10 + 18 dB) combined with 32 dB). Now the worst-case measurement uncertainty is reduced to +2.5 dB, -1.9 dB, which is much more reasonable.

One-port calibration can be used effectively without any series attenuation under some circumstances. For example, when measuring the input match of amplifiers with high reverse isolation, the amplifier's isolation essentially eliminates the effect of imperfect load match.

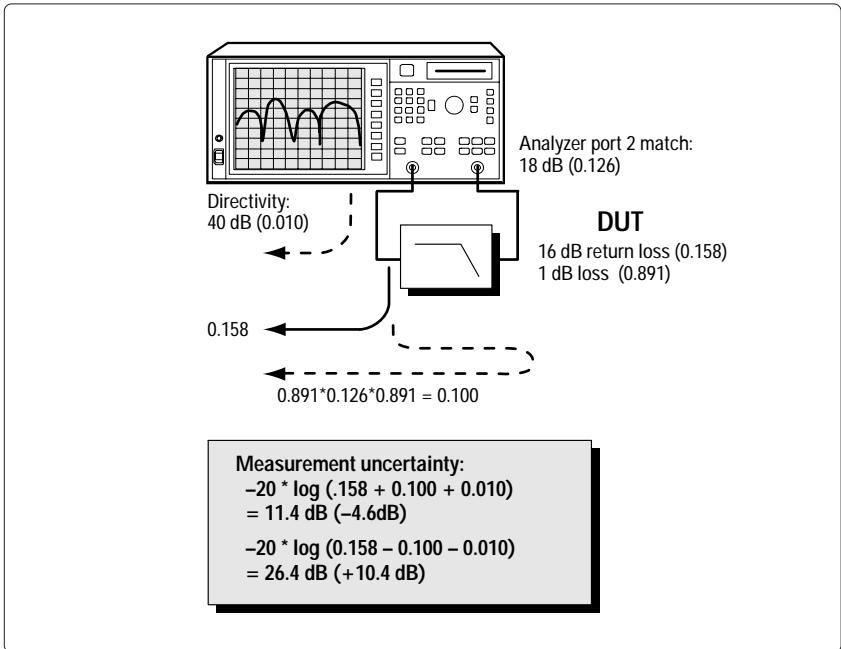


Figure 5a. Proper termination is important to keep measurement uncertainty reasonable.

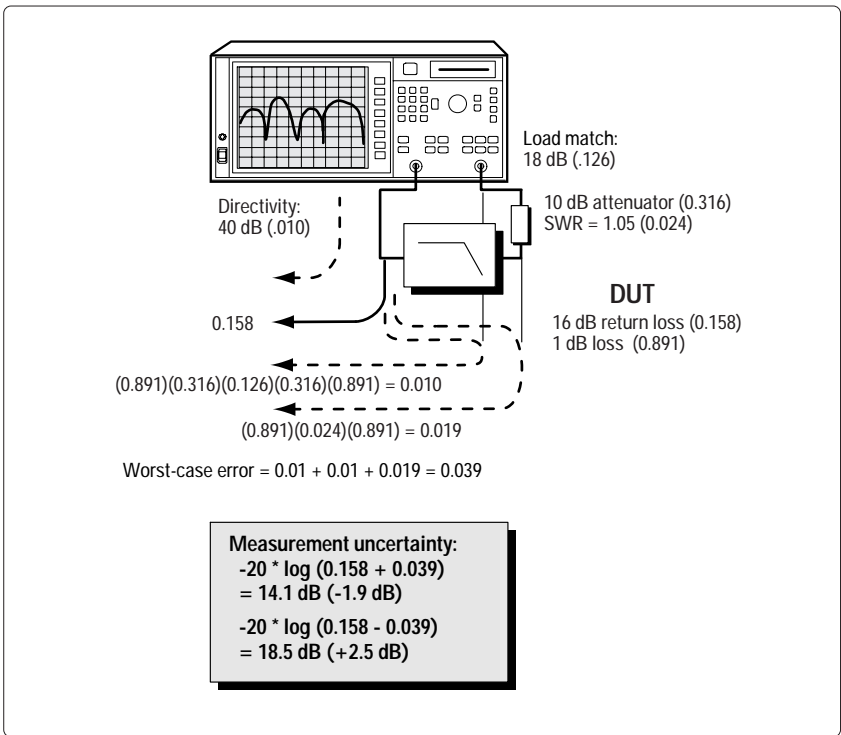


Figure 5b. Improved load matching reduces measurement uncertainty.

Using Frequency-Offset Mode to Accurately Measure Mixers, Converters, and Tuners

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

For higher accuracy, some VNAs offer a frequency-offset mode that allows the frequency of the internal RF source to be arbitrarily offset from the analyzer's receivers. Narrowband detection can be used with this mode, providing high dynamic range and good measurement accuracy, and also the ability to measure phase and group delay.

There are two basic ways that frequency-offset mode can be used. The simplest is to take the output from the mixer or tuner directly into the reference input

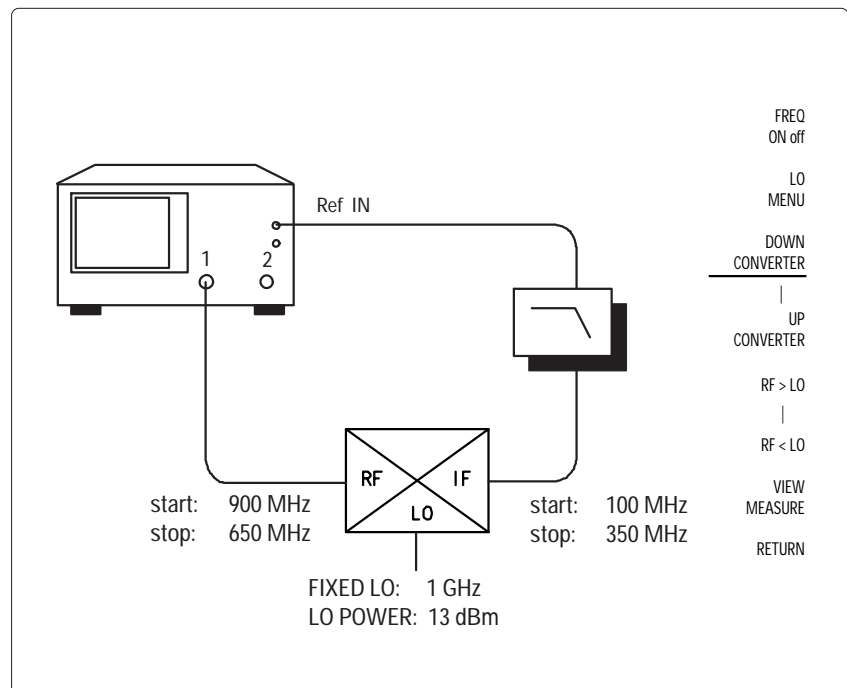


Figure 6a. High-dynamic-range amplitude measurements of mixers using frequency-offset mode

on the analyzer (as shown in figure 6a). 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.

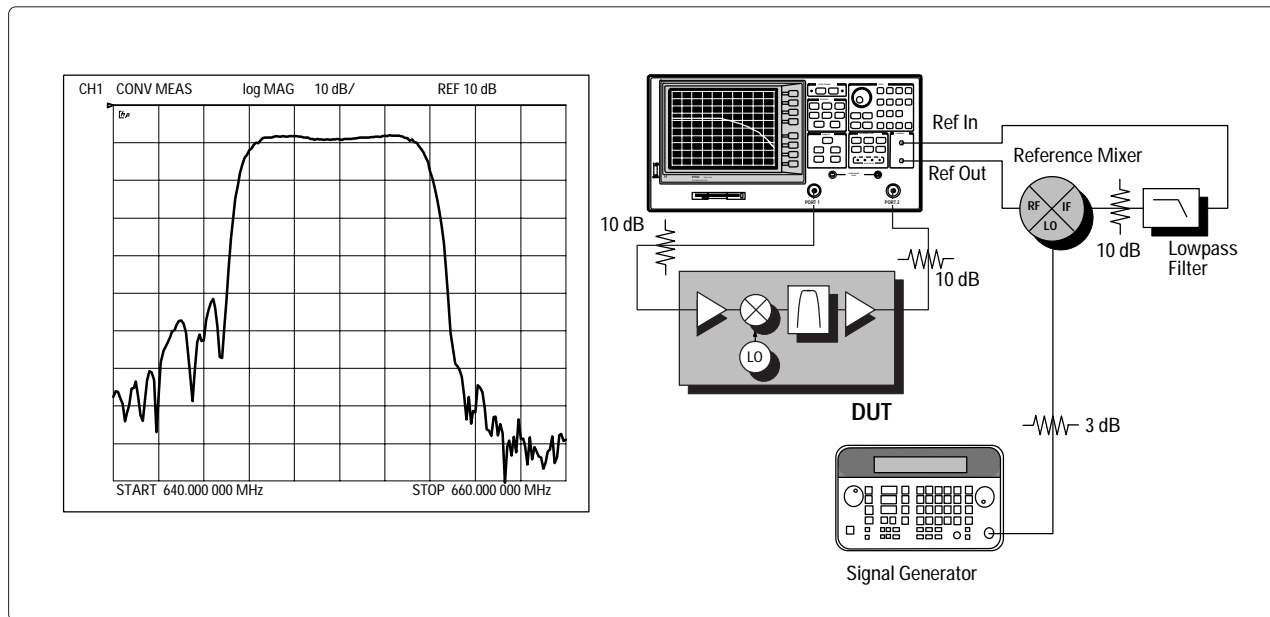


Figure 6b. Increasing dynamic range with a reference mixer

For high-dynamic-range amplitude measurements, a reference mixer must be used (figure 6b). This mixer provides a signal to the R channel for proper phase lock, but does not affect measurements of the DUT as it is not in the measurement path. A reference mixer must also be used for phase or delay measurements. 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.

Increasing Accuracy When Measuring Noninsertible Devices

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 when measuring a device that has poor output match, such as an amplifier or a low-loss device.

There are five basic ways to overcome the potential errors when making a through connection for a noninsertible device:

1. Use electronic calibration (ECal) modules. Using an ECal module with the connectors that match the DUT is the simplest and fastest noninsertible calibration method. Full two-port error correction, defined at the test ports, is achievable.
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 cal-

culates 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 works reasonably well 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 will be no better than the raw load match. As the through length approaches one-quarter of a 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 the “swap equal adapters” method. For this method you use two matched adapters of the same electrical length, one with male/female connectors and one that matches the DUT.

For example, 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 (you now have two male test ports), and do the reflection portion of the calibration. 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). This process is shown in figure 7.

4. Modify the through-line standard. If your application is manufacturing test, the requirement of the swap-equal-adapters method for additional adapters may be a drawback.

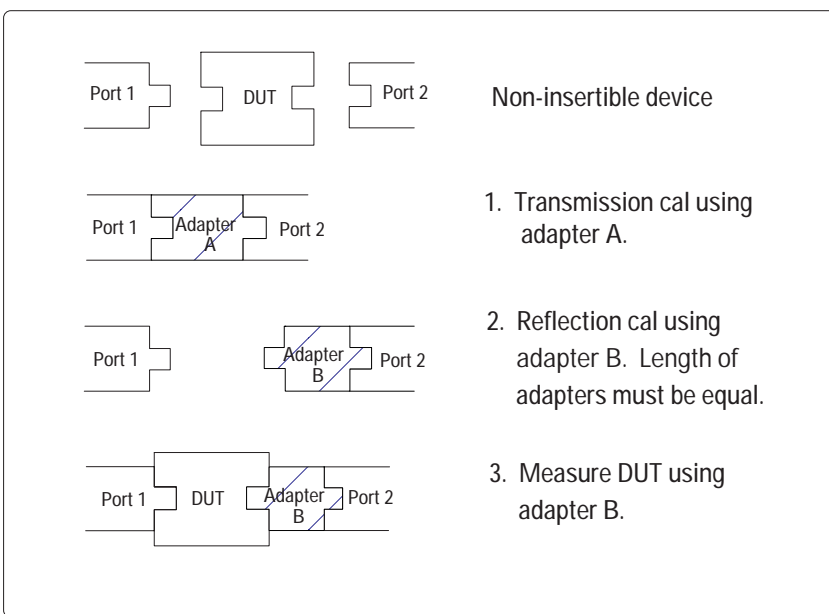


Figure 7. Swap-equal-adapters method for measuring noninsertible devices

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-adapters calibration, ending up with test ports that are either both female or both male. 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 VNA 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.

Selecting the Appropriate Measurement Parameters to Prevent Aliasing Problems

When measuring a DUT that has a long electrical length, you need to select the appropriate measurement parameters carefully. A 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 the wheel appears to spin backward because the number of frames per second is too low to accurately portray the motion.

Furthermore, the VNA calculates group delay data from phase data. If the slope of the phase is reversed, 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 measurement, try decreasing the spacing between frequency points (by increasing the number of points or reducing the frequency span) and see if the data on the VNA's display changes.

Figure 8a shows a measurement of a SAW bandpass filter on a network analyzer with 51 points in the display. The indicated group delay is negative—a physical impossibility. But if the

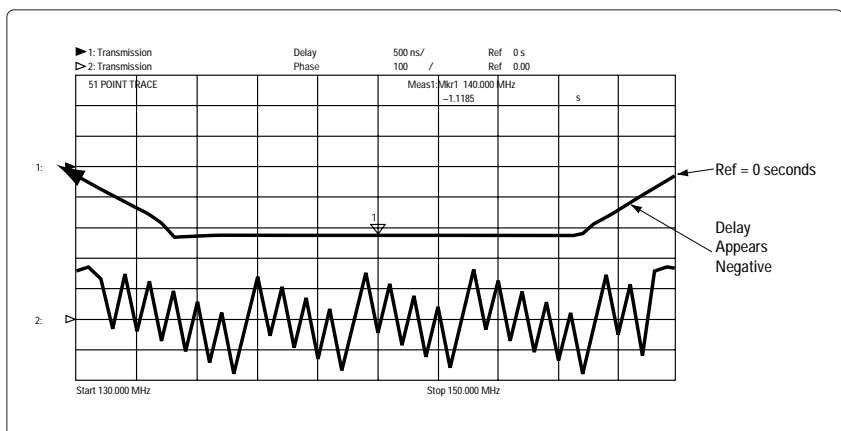


Figure 8a. Decreasing the spacing between frequency points can create an aliasing problem. In this case, the display used 51 points.

number of display points is increased to 201, as in figure 8b, it becomes clear that the VNA settings created an aliasing problem.

Quickly Verifying a Network Analyzer's Calibration or Performance

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, there are several "quick check" methods you can use to verify an instrument's calibration or performance. All you need are a few calibration standards.

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

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).

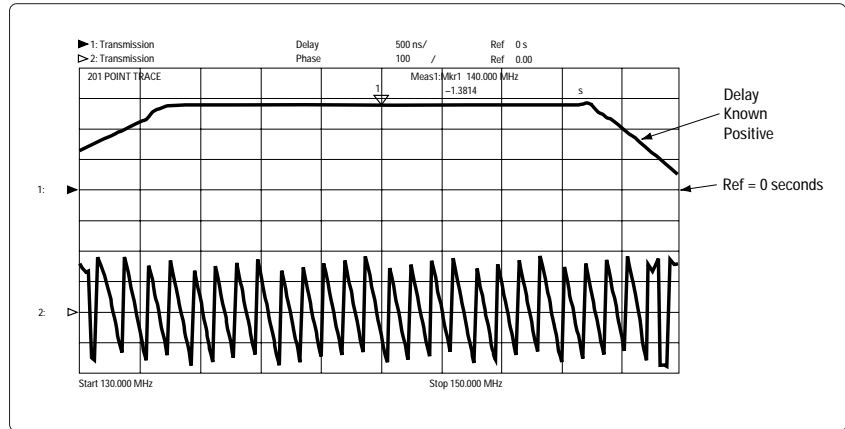


Figure 8b. The same data with 201 points shows that the VNA settings created the aliasing problem.

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. These verifications could also be done immediately after a calibration to verify its quality. 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.

Using a Segmented Sweep to Increase Accuracy at Fast Sweep Speeds

Tuning and testing RF devices in a production environment often require speed and accuracy from a network analyzer. However, at fast sweep speeds an analyzer's optimum accuracy may be unavailable. Many network analyzers have the ability to define a sweep consisting of several individual segments. Each segment can have its own start and stop frequency, number of data points, IF bandwidth, and power level. Using a segmented sweep, the measurement can be optimized for speed and dynamic range.

Data resolution can be made high where needed (with more data points) and low where not needed (with fewer data points); frequency ranges can be skipped where data is not needed at all. The IF bandwidth can be large where high dynamic range is not necessary, decreasing the sweep time, and small where 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 cellular-phone base-station receiver filter/LNA combination). **Figure 9**

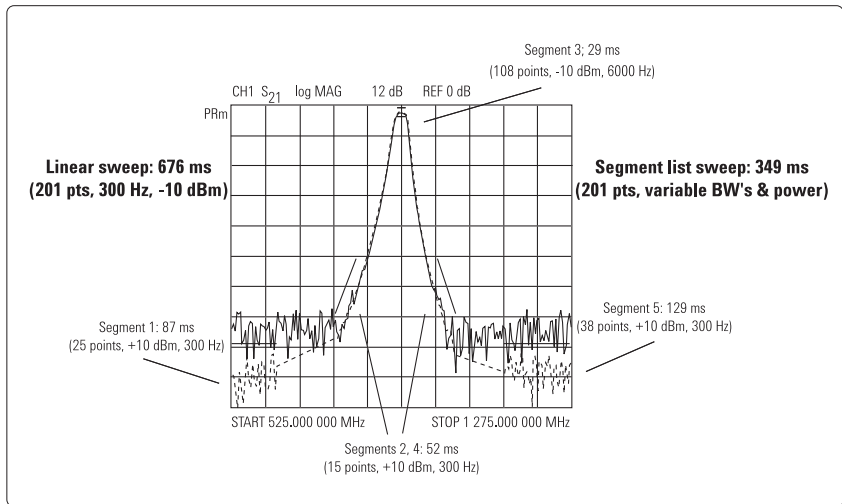


Figure 9. Segmented sweep compared to a linear sweep

shows a filter/amplifier combination where the sweep time and dynamic range are considerably better using a segmented sweep than they would be using a linear sweep, where the IF bandwidth and power level are fixed.

Extending the Dynamic-Range Measurement Capability of the Network Analyzer

You can extend the dynamic-range measurement capability of your network analyzer by bypassing the coupler at test port 2 (for forward transmission measurements). Because the coupler is no longer in the measurement path, the associated loss through the coupled

arm no longer impacts the measurement, increasing the effective sensitivity of the analyzer. However, with the coupler out 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, with the power set high in the stopbands (typically +10 dB) and low in the passband (typically -6 dB).

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 10). 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. As both forward and reverse measurements are possible, it is still possible to apply full two-port correction.

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 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.

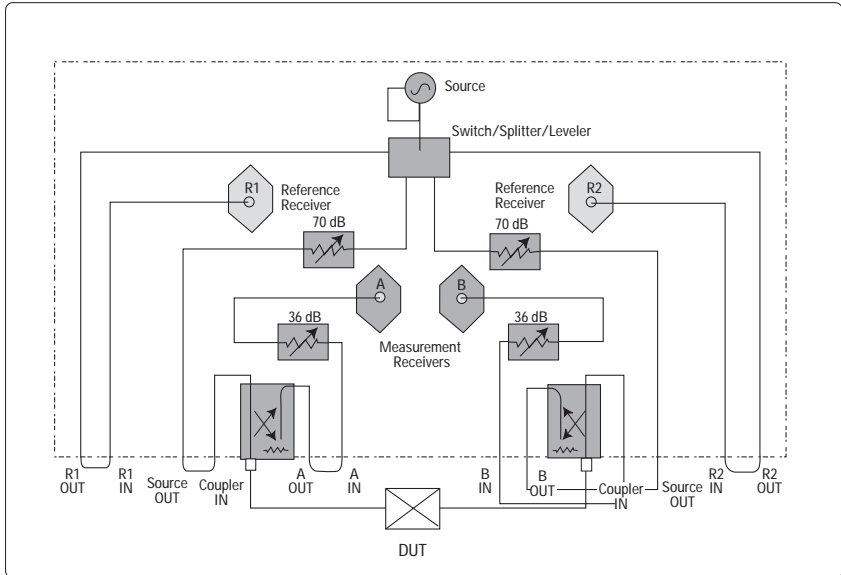


Figure 10. Extending dynamic range by reversing the port 2 coupler

While ideal balanced components only respond to or produce differential (out-of-phase) signals, real-world devices also respond to or produce common-mode (in-phase) signals. Newer analyzers provide built-in firmware and/or software packages that perform a series of single-ended stimulus/response measurements on all measurement paths of the DUT, and then calculate and display the differential-mode, common-mode, and mode-conversion S-parameters.

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