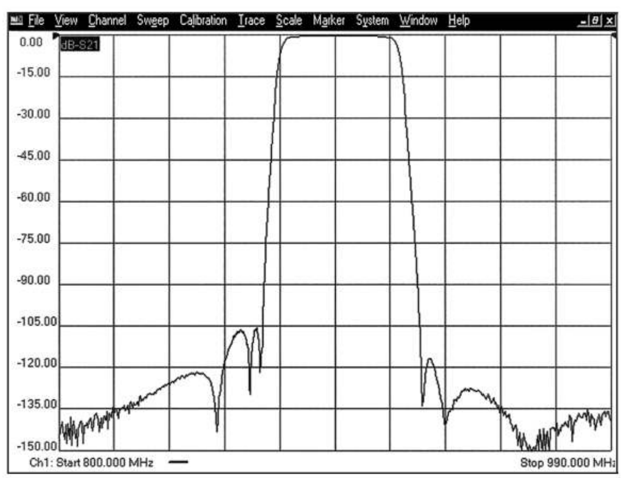
Keysight Technologies
Understanding and Improving Network Analyzer Dynamic Range

Application Note



KEYSIGHT TECHNOLOGIES

Introduction

Achieving the highest possible network analyzer dynamic range is extremely important when characterizing many types of microwave devices, and in some cases the key factor in determining measurement performance. To achieve the greatest dynamic range from a network measurement system, it is important to understand the essence of dynamic range and the methods that can be employed to increase it. Armed with this knowledge, the designer can choose the method that achieves the best results with the least impact on other instrument parameters such as measurement speed.

Network analyzer dynamic range is essentially the range of power that the system can measure, specifically:

- P_{max} : The highest input power level that the system can measure before unacceptable errors occur in the measurement, usually determined by the network analyzer receiver's compression specification.
- P_{ref} : The nominal power available at the test port from the network analyzer's source.
- P_{min} : The minimum input power level the system can measure (its sensitivity), set by the receiver's noise floor. P_{min} depends on the IF bandwidth, averaging, and the test set configuration.

The two common definitions for dynamic range are:

- Receiver dynamic range = $P_{max} - P_{min}$
- System dynamic range = $P_{ref} - P_{min}$

Achievable dynamic range depends upon the measurement application as shown in Figure 1.

- *System dynamic range*: The dynamic range that can be realized without amplification such as when measuring passive components such as attenuators and filters.
- *Receiver dynamic range*: The system's true dynamic range if it is considered a receiver. An amplifier may be required to realize the receiver's full dynamic range. This can be the device under test or an external amplifier added to the measurement system.

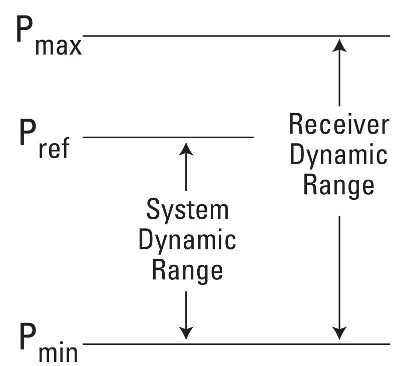


Figure 1.

Noise floor defined

The receiver's noise floor is an important network analyzer specification that helps determine its dynamic range. Unfortunately, “noise floor” is not a well-defined term and it has been defined several ways over the years.

The results of an experiment to compare some common noise floor definitions are shown in Figure 2. In this experiment, Gaussian random noise with a noise power of –100 dBm was simulated, and the noise floor was calculated using four definitions:

- The solid line shows the RMS value of the noise, which is equal to the noise power of –100 dBm.
- The dashed line (–101 dBm) is the mean value of the linear magnitude of the noise, converted to dBm.
- The dotted line (–102.4 dBm) is the mean value of the log magnitude of the noise.
- The dot-dash line (–92.8 dBm) is the sum of the mean value of the linear magnitude of the noise and three times its standard deviation, converted to dBm.

Keysight Technologies’s new PNA series vector network analyzers use the RMS value to define receiver noise floor. This is a commonly used definition, and is easy to understand because it is the receiver's equivalent input noise power.

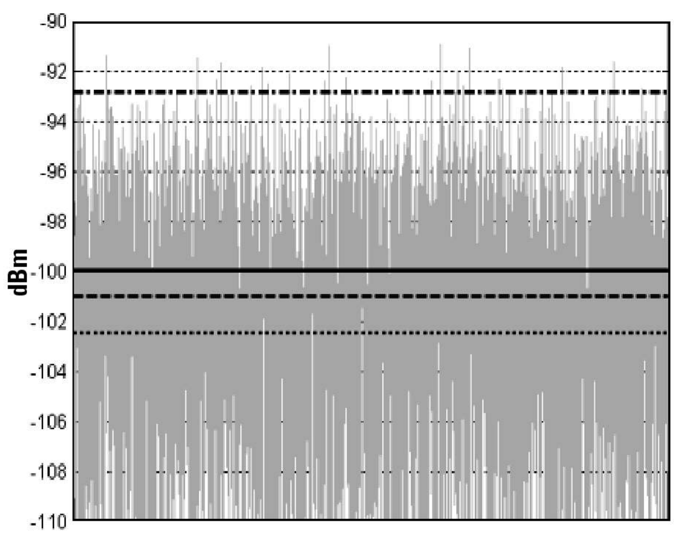


Figure 2. Various noise floor definitions

Improving dynamic range

In some measurement situations, it is desirable to increase the network analyzer’s dynamic range beyond the level obtained with the default settings. Noise floor sets the minimum power level that the instrument can measure and thus limits its dynamic range. Noise floor can be improved by using averaging, or by reducing the system bandwidth (IF BW).

Smoothing is another technique that is often considered to be akin to averaging and IF BW adjustment, but it does not reduce the noise floor. Smoothing is adjacent-point averaging of the formatted data, similar to video filtering. Trace-to-trace (or sweep-to-sweep) averaging operates on the pre-formatted, vector data, so that it can actually reduce the noise power. This key difference is responsible for the inability of smoothing to reduce noise floor, although it does reduce small peak-to-peak variations of noise on a trace.[1]

Averaging

The PNA Series and many other network analyzers perform sweep-to-sweep averaging by taking an exponentially weighted average of the data points from each sweep. Exponen-tially weighting the samples in the data set allows averaging to proceed without termination, even after the desired averaging factor has been reached. The averaging is performed on complex data, which means that the data is averaged vectorially.

Many signal analyzers use scalar averaging, which mitigates only the variance of the noise but does not affect the average noise level. When a trace that contains both coherent signal and uncorrelated noise is averaged in the vector sense, the noise component will approach zero, and the resulting trace will show the desired signal with less noise present. When viewed with the log magnitude format on the network analyzer display, it becomes clear that the average noise level is reduced and an improvement in dynamic range is achieved.

Using the averaging function available in most vector network analyzers, signal-to-noise ratio is improved by 3 dB for every factor-of-2 increase in averages. This is a powerful method for reducing noise floor. However, it also reduces measurement speed because when two traces must be averaged, measurement time doubles.

Averaging can only be used on ratioed measurements, and will not work on measurements using a single receiver channel. Averaging is not allowed on unratioed measurements because phase is random in this mode and averaging (which is performed in the complex domain), will always cause the result to approach zero.

IF BW reduction

The IF BW of the system can be altered via the front panel or remote programming, and its value will affect the digital filtering that is performed on the data collected in the analyzer's receivers. Decreasing IF BW will reduce noise floor by filtering out noise that is outside the bandwidth of the digital filter.

The low level noise that is present in the analyzer's receiver chain is caused by thermal noise arising from the thermal agitation of electrons in resistances. Consequently, it is directly proportional to bandwidth. The mean-square value of the thermal noise voltage is given by:

$$E^2 = 4RkTB$$

where

- k is Boltzmann's constant (1.38 e-23 joules/Kelvin)
- T is the absolute temperature in degrees Kelvin
- R is the resistive component in ohms
- B is the bandwidth in Hertz

The noise power delivered to a complex conjugate load is

$$Pn = \frac{E^2}{4R} = kTB$$

This is the familiar 'kTB' relationship for noise power[2].

Noise is random in nature and is considered nondeterministic because it is caused by a collection of small events and exhibits a Gaussian probability distribution (which can be proved by the central limit theorem[3]).

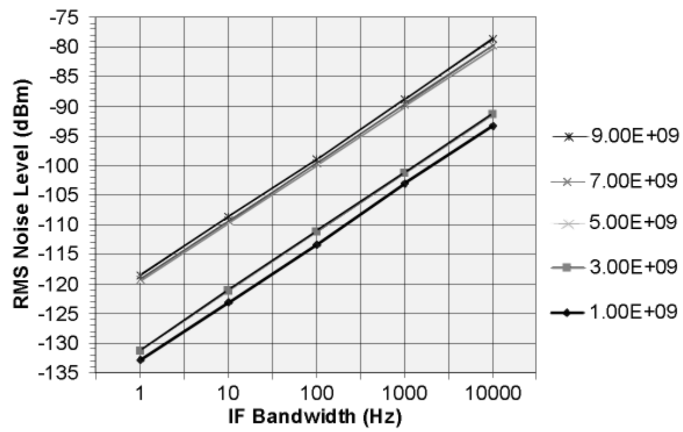


Figure 3. RMS noise floor vs IF BW (n=801 pts)

A high level of confidence in the relationship between noise floor and IF BW makes it possible to precisely calculate the noise floor reduction achieved by decreasing the IF BW. An empirical study was performed using the PNA network analyzer in which the RMS noise level was measured at 5 different CW frequencies (1, 3, 5, 7, and 9 GHz). There were 801 points in the sweep and the IF BW was set to 1 Hz, 10 Hz, 100 Hz, 1 kHz, and 10 kHz. The noise floor of the VNA was measured with no signal present at the test ports. In Figure 3, the observed relationship between the noise floor and the IF BW shows that the PNA's RMS noise floor very closely follows the theoretical expectation. Deviation from theory is negligible.

As with averaging, decreasing IF BW to reduce noise floor reduces measurement speed. While it could be expected that a factor-of-10 decrease in IF BW will reduce the noise floor by 10 dB and will cause a factor-of-10 increase in measurement time, this is not always true because the digital filters used in a network analyzer at different IF bandwidths may vary in shape. In the PNA Series for example, sweep time increases by a factor that is less than 10 for a factor-of-10 reduction in IF BW. This means that to achieve the same reduction in noise floor, IF BW reduction will reduce measurement speed less than will averaging.

Choosing the best method

To achieve noise floor reduction, averaging can be increased or IF BW reduced. If measurement speed is not of paramount concern, either method will work equally well. The time required to acquire and process data for a trace (called cycle time), includes not only sweep time, but also retrace time, band-crossing time, and display update time.

Since averaging requires taking multiple traces and updates the display every time, it generally takes slightly longer to use averaging than IF BW reduction, especially if many averages are required. It is important to remember that much of the difference in impact on measurement time is caused by the digital filtering performed for the various IF BWs. This effect manifests itself in the sweep time component of the cycle time, so to determine the effect of the two noise-floor-reduction methods on measurement time, it is appropriate to consider sweep time only.

Consider the PNA Series set up in a 10 KHz IF BW. If an improvement of 10 dB is desired in dynamic range, it can be achieved by averaging 10 sweeps or setting the IF BW to 1 KHz. Table 1 shows the effect on sweep time for the two approaches to achieve a dynamic range improvement of 10 or 20 dB.

Table 1 Sweep time impact with fast IF BWs

		Noise floor reduction (dB)	Sweep time increase factor
10 KHz	10 averages	10	10
1 KHz	0 averages	10	7.75
10 KHz	100 averages	20	100
100 Hz	0 averages	20	74.8

This example uses a fairly fast IF BW, and shows that IF BW reduction produces a benefit over averaging when attempting to improve dynamic range. However, now consider a slower sweep mode (i.e., lower IF BW). If the PNA is set at an IF BW of 100 Hz and a noise floor reduction of 10 dB is desired, averaging with a factor of 10 can be applied, or the IF BW can be reduced to 10 Hz. Table 2 shows the impact on sweep time.

Table 2 Sweep time impact with slow IF BWs

		Noise floor reduction (dB)	Sweep time increase factor
100 Hz	10 averages	10	10
10 Hz	0 averages	10	9.9
100 Hz	100 averages	20	100
1 Hz	0 averages	20	99.5

The increase in cycle time closely parallels the increase in sweep time, and it is evident that using IF BW reduction to attain increased dynamic range has an advantage over averaging in terms of impact on measurement speed if the network analyzer is in a fast sweep mode. With a slow sweep mode, impact on measurement speed is essentially the same for either of the two methods.

There are other factors that can be considered when deciding which method to choose for increasing dynamic range in a given measurement application. Using averaging to reduce noise floor allows the user to observe the traces on the PNA screen as the averaging progresses, which some designers may find useful. IF BW reduction works on both ratioed and unratioed measurements (unlike averaging which only works in ratioed mode), which can be the determining factor in some situations.

The PNA Series provides a large number of IF BWs to choose from, which gives the designer wide flexibility in desired noise floor reduction while incurring the smallest possible reduction in measurement speed. In many situations, dynamic range can be increased by using both averaging and IF BW adjustment.

Dynamic range, segmented sweep and the configurable test set

For applications in which speed and wide dynamic range must both be optimized, the segmented sweep feature available on some network analyzers is useful. This feature is extremely valuable when measuring filters that demand simultaneous characterization of the passband at a high power level, and the reject band at a very low power level. Segmented sweep allows the user to break a frequency sweep into multiple segments, each with its own stop and start frequency, IF BW, power level, and number of points. When measuring a filter, the IF BW in the passband can be set wider for a fast sweep rate, as long as high level trace noise is kept sufficiently small.

In the reject band, where noise floor contributes significantly to measurement error, the IF BW can be set low enough to achieve the desired reduction in average noise level. To increase the dynamic range of the analyzer even further, segmented sweep can be used in conjunction with a re-configuration of the test-set (Figure 4). An increase in dynamic range of 12 to 15 dB can be achieved with this method by reversing the directional coupler in the receiving test port.

Summary

Network analyzer dynamic range is the most critical parameter in many measurement situations, and it can be increased by reducing noise floor through averaging or IF BW reduction. However, each method has disadvantages that determine its suitability in certain cases, and has a unique effect on measurement speed. Beyond these two methods, further dynamic range improvement can be obtained and measurement speed retained by using the segmented sweep feature found in network analyzers such as Keysight's PNA Series, as well as a configurable test set.

References

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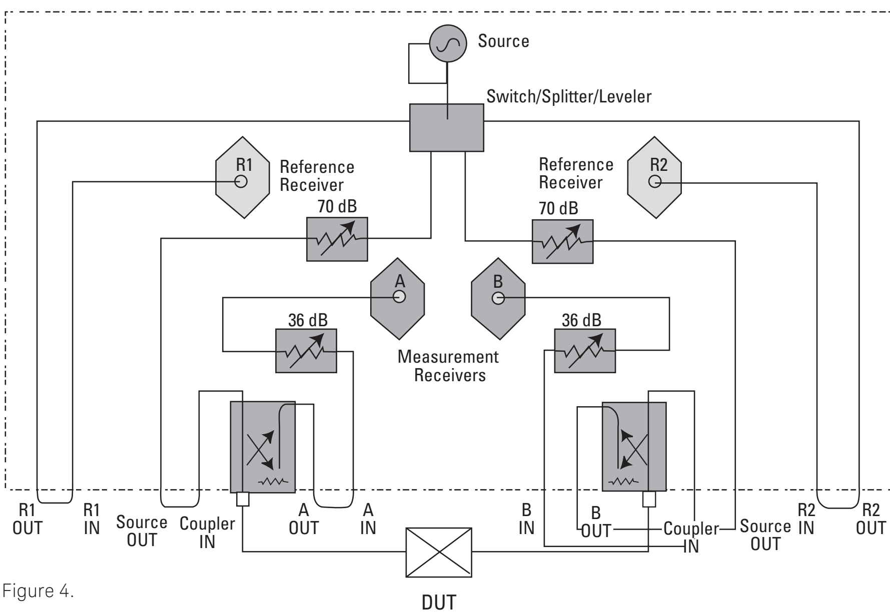

Figure 4.

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