The Basics of Noise Figure Measurements for ATE

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Introduction

Noise figure measurements are essential to ensure that minimal noise is added to the receiver chain of the device. Once additional noise joins the signals, receiver performance will be degraded. In extreme cases, it is no longer possible to distinguish the legitimate signal from the noise. The signal and noise get processed together. Attempts to amplify the signal level, for example, will raise the noise level by an equal amount.

There are two primary techniques used to perform noise figure measurements on these devices with automated test equipment (ATE); Y-Factor and Cold Noise (or Gain) methods. Differences between making measurements on RF-to-RF devices and RF-to-baseband devices are discussed in this article.

The Definition of Noise Figure

Noise figure[1] describes the degradation of the signal-to-noise ratio (SNR) through a device. It is defined as the (logarithmic) ratio of input SNR to output SNR at a standardized reference temperature, $T = T_0$, designated by IEEE to be 290K (~17°C) [1].

$$NF = 10\log\left[\left.\frac{S_i/N_i}{S_o/N_o}\right|_{T=T_0=290K}\right] \tag{1}$$

where S and N are signal and noise voltage levels, like those that would be measured on an ATE digitizer.

Temperature comes into the definition because the dominant contribution of noise in electronics is caused by thermal agitation of the electrons in conductive media of the devices, a.k.a. thermal noise. Figure 1 depicts Equation (1), showing this impact of noise on a device. It shows the input power level of a device with amplification (having a gain, *G*) and the increased noise at the output of the device resulting in a decreased signal-to-noise ratio. Note that both, input signal and input noise are amplified by the device, and are higher at the output of the device. However, since the device adds noise the total noise at the output is raised significantly.

[1] Many times a term, noise factor, is introduced in place of noise figure. Noise factor, F, is simply the linear (unitless) representation of noise figure. It is rarely seen in data sheets and specifications. It is important not to get the terms Noise Figure and Noise Factor mixed as they are completely different.

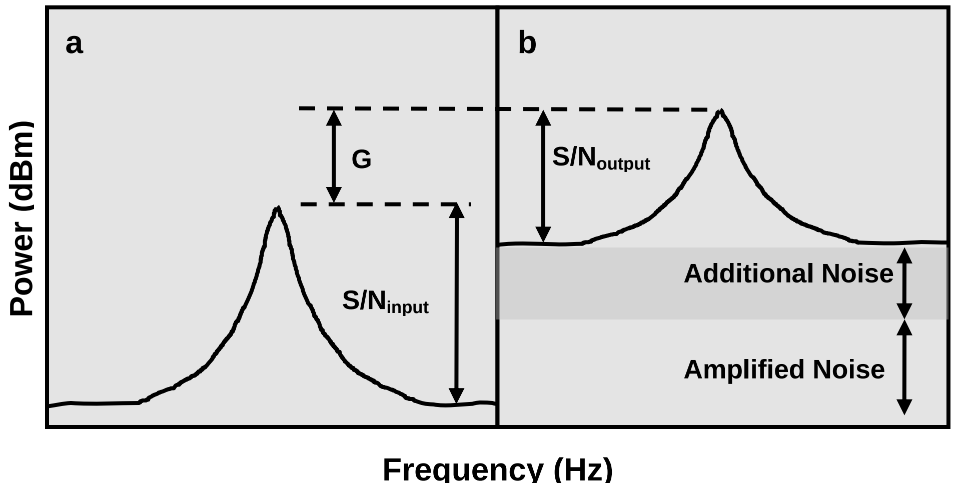

Figure 1 Signal-to-noise degradation of a signal passing through a semiconductor device. The input signal (a) has low peak power and good signal-to-noise properties. The output signal (b) has a higher peak amplitude, but also an increased noise floor, giving overall poor signal-to-noise performance.

Noise Figure Measurement Methods

There are 2 primary methods of measuring Noise Figure: the Y-Factor Method & the Cold Noise Method. Both methods are described below.

The Y-Factor Method

The Y-Factor method [2] of measuring noise figure is the method that is used *behind the scenes* in most noise figure meters and analyzers. It involves applying a noise source to the input of the DUT and making noise power measurements at the output of the DUT. By doing this, a ratio of noise power measurements, the Y-Factor, is determined and noise figure is derived from that.

The Y-Factor method uses a noise source applied to the input of the DUT as shown in Figure 2. It is powered on and then off. Each time, a power measurement at the output of the DUT is performed. The Y-Factor is defined as the ratio of “hot” to “cold” measured noise power (in Watts),

$$Y = \frac{P_{hot}}{P_{cold}} \tag{2}$$

The term “hot” refers to the state of the noise source being powered on and adding noise to the device, much like a signal generator providing a voltage or power signal to the input of the device. “Cold” refers to the noise source being powered off, but still connected to the input of the DUT[2]. The standard for almost all noise sources is that in their "off," or "cold" state, they provide a 50–ohm termination to the input of the DUT[3].

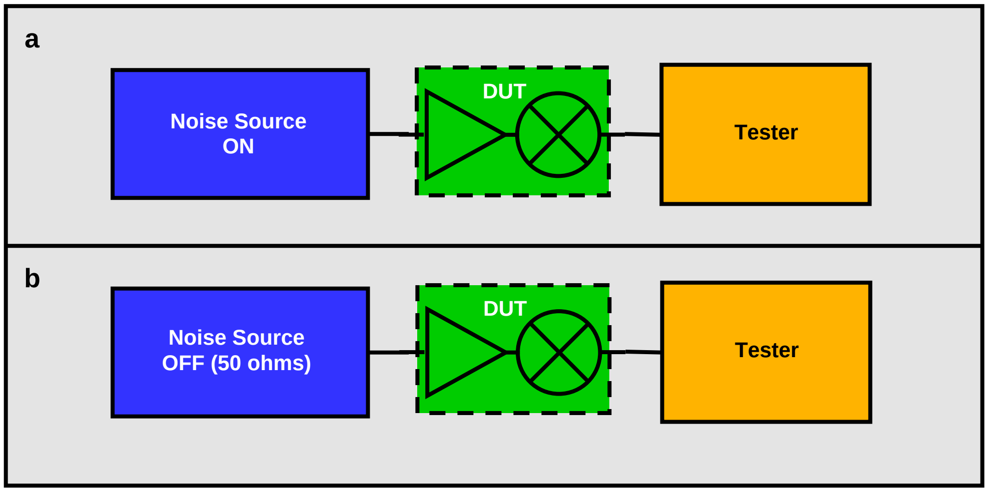

Figure 2 A noise source is applied to the DUT and the resulting output noise powered is measured by the tester. a. The noise source is powered on and provides "hot" noise related to its *ENR*. b. The noise source is powered off, providing a 50-ohm "cold" termination to the input of the DUT.

Every noise source has an associated parameter termed *excess noise ratio*, or *ENR*. *ENR* is the power level difference between hot and cold states, compared to the thermal equilibrium noise power at the standard reference temperature, T_0 (again, 290K). Also, as previously mentioned, in modern practice the cold noise state is almost always the noise source in its powered-off state. This allows *ENR* to be simply defined as,

$$ENR = \frac{T_h}{T_0} - 1 . \qquad (3)$$

Diode-based noise sources come calibrated, with a statement of their *ENR* value.

Using the measured Y-Factor along with the *ENR* of the noise source, noise figure is calculated as,

$$NF = 10\log_{10}\left[\frac{ENR}{(Y-1)}\right] \qquad (4)$$

where ENR and Y are linear (unitless) values and

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[2] The nomenclature, *hot* and *cold*, stems from the earliest experiments with noise where a resistor resting in either a heated chamber or cooled bath of liquid was used as a noise source.

[3] This 50-ohm impedance is termed *characteristic impedance*, with 50 ohms being the standard for nearly all RF applications. Cable television and FM radio industries often use 75-ohms as the standard characteristic impedance. This work assumes 50 ohms throughout.

$$NF|_{\mathrm{dB}} = 10\log_{10}(F) = ENR|_{\mathrm{dB}} - 10\log_{10}(Y\text{-}1). \quad (5)$$

Y is usually much greater than 1 so that the "-1" in (5) can be ignored providing a simple equation,

$$NF|_{\mathrm{dB}} \approx ENR|_{\mathrm{dB}} - (P_{hot,\,\mathrm{dB}} - P_{cold,\,\mathrm{dB}}), \quad (6)$$

where $P_{hot,\,\mathrm{dB}}$ and $P_{cold,\,\mathrm{dB}}$ come from (2). Both, Equations (5) and (6) are commonly used for measuring noise figure when using a noise diode built into the ATE, RF AWG (arbitrary waveform generator) noise source, or noise diode on the load board.

In the V93000 PSRF system, the RF AWG can be use to generate the noise required. The advantage of this is that ENR can be easily adjusted by software.

The Cold Noise Method

The Cold Noise, or Gain, method [1] [3] is another technique that is considered to be very production test-friendly for RF-to-baseband devices. It relies on measuring just the cold noise power of the DUT when a 50-ohm termination is applied to its input. This method also requires the gain of the device to be measured. The benefit of this is that it is common practice to place this test after the gain test in the production test program. In this way, effectively, only one measurement (noise power) has to be made. Having these two values, gain and noise power, the noise figure is calculated as,

$$NF\big|_{dB} = 10\log_{10}\left[\frac{P_{cold}}{kTBG}\right] \quad (7)$$

and,

$$NF|_{dB} = P_{cold} - (\text{-174dBm/Hz}) - 10\log_{10}(B) - G|_{\mathrm{dB}}. \quad (8)$$

B is the bandwidth over which the cold noise power measurement, P_{cold}, is made. The value, -174dBm/Hz, is the thermal noise power associated with the temperature 290K. It is the product, kT ($1.38\text{x}10^{-23}$J/K * 290K), converted to logarithmic format, in dBm.

In the V93000 PSRF system, the P_{cold} measurement can simply be obtained by terminating the device input with a 50ohm load.

Comparing the Two Methods

The Y-Factor method has the advantage of taking two power measurements and using the ratio of these two measurements to calculate noise figure. Since it uses these in a ratio, the measurements are relative and it allows the absolute power accuracy of the measurement equipment to be of less concern. The primary disadvantage is that it often utilizes a diode-based, fixed-*ENR* noise source (this disadvantage will be demonstrated in a later section of this article) which can be problematic when measuring either very high, or very low noise figure values [3]. The reason for this can be seen from Equation (5). If the noise figure is too large (relative to the *ENR* of the noise source), the measured hot noise power causes Y to approach unity and hence can yield a different than expected noise figure. When a diode-based noise source is used it has a fixed *ENR*. This *ENR* may be suitable for some devices, but not others, specifically with larger noise figure as described above. In some cases, an AWG noise source has been used [4] [5]. The AWG noise source provides an adjustable *ENR* to combat this situation.

The Cold Noise method has the advantage that it only requires one power measurement to be made (since the gain of the DUT has been determined in a test prior to the noise figure test). Because of this, the Cold noise method's accuracy and repeatability track that of the power measurement.

Both methods perform a cold noise power measurement (with the input of the DUT terminated in 50 ohms). A methodical difference is the hot noise power measurement of the Y-Factor method. This hot noise power measurement provides a means to calculate the gain of the DUT, in addition to noise figure. This is how a noise figure meter or spectrum analyzer is able to display both, gain and noise figure, over frequency.

Choosing a Noise Figure Measurement Method

Device settings having high gain (with low or high noise figure) are the easiest to measure, with either method, Cold Noise or Y-Factor, working well. The common rule of thumb is that the higher the sum of gain and noise figure (in dB), the easier the noise figure measurement can be made. One caveat in these devices is that for those devices that have both, high gain and high noise figure, in order to use the Y-Factor method one must use a noise source having a higher *ENR*[4].

Both methods becomes a little weak in the case of low gain, low noise figure devices because the tester's own noise becomes significant relative to the noise of the DUT. This primarily affects the cold noise measurement in both methods. For this special class of conditions, neither method is very easy to implement in production and would likely require a pre-amplifier to reduce the effective noise figure of the tester [2]. Fortunately, for RF-to-baseband devices, this combination of low gain and low noise figure is not a common set of conditions.

In the case of low gain, high noise figure devices, the only caution is, again, that the Y-factor method with a fixed-*ENR* noise source can become inaccurate if its ENR is not large enough because the noise output from the DUT is significantly greater than the noise of the noise source and *Y* approaches unity (Equation (5)).

[4] This assumes typical noise sources, traditionally used for RF-to-RF testing having *ENR* values of 12-22dB.

	Suitable Application	Advantages	Disadvantages
Cold Noise	High Gain and/or High NF	High through-put, easy setup	Not suitable for low G or low NF
Y Factor	Various Gain or NF	Flexible, suitable for various gain & NF Ratio of two measurements provides excellent accuracy (relative measurements)	Lower through-put. Will need varying ENR sources. Not suitable for low NF or very high NF[5]

Table 1 Summary of the different NF measurement methods.

Considerations for ATE and Production Noise Figure Measurements

Noise figure measurements involve the analysis of low-level signals. One of the key ATE requirements for noise figure is that the receiver noise floor is sufficiently low to measure these signals. On the stimulus side, the system should not have spurs that may unintentionally, saturate the device's input.
There are many other possible sources of error that can be introduced. Fortunately, for production of modern RF devices, these items end up being of less concern. Remember, when making *production* noise figure measurements, the goal is not necessarily to characterize noise figure to find the absolute, most-accurate value possible. It is to find a meaningful and repeatable result that correlates to a noise figure measurement that has been made on a bench test setup. Some things that that can add to inaccuracies of the noise figure measurement are listed below. References [2] and [3] discuss each of these, and how they contribute to inaccuracies and the uncertainty of noise figure measurements in detail.

When performing noise figure measurements in a production environment there are a couple additional items that must be considered,

- Repeatability vs. Accuracy
- Averaging of Noise Power Measurements
- Measurement Bandwidth
- Variation of Temperature
- Noise Figure of the ATE
- Impedance Matching of DUT to Tester

[5] This statement assumes that a noise figure measurement system/setup has a fixed-ENR noise source of around 15dB.

Some of these are discussed in reference to the limitations and assumptions imposed by ATE and the ATE environment, constantly striving to reduce cost of test. Others are topics that highlight deviations from traditional RF-to-RF function testing on the bench. Some of these changes and variations are arising due to the inevitable integration of device technology in which the measurements being performed are no longer just simply functional block tests, but rather controlled by their application-specific requirements.

Summary

Fundamentals of the concept of noise figure and making noise figure measurements have been discussed. The two primary methods, Y-Factor and Cold Noise were presented along with when and where each method makes the most sense to use.

The references cited in this article also serve as recommended reading. They are great resources to provide detailed information on the topics discussed here. References [6]-[10] have been added as suggested reading.

References

[1] Hewlett Packard, "Fundamentals of RF and Microwave Noise Figure Measurements," Application Note 57-1 (1983).
[2] Hewlett Packard, "Noise Figure Measurement Accuracy: The Y-Factor Method," Application Note 57-2 (1992).
[3] Kelly, J., "HVM Receiver Noise Figure Measurements," Verigy Technical Note (2008).
[4] Kelly, J., Kara, M., Heistand, T., and Goh, F., "Arbitrary Waveform RF Noise Source for Production Noise Figure Measurements," *Proceedings of European Test Symposium 2004* (2004).
[5] System for Measuring Noise Figure of a Radio Frequency Device, US Patent 6,114,858.
[6] Agilent Technologies, "Agilent Preamplifiers and System Noise Figure," Agilent Application Note (2006).
[7] Agilent Technologies, "Practical Noise Figure Measurement and Analysis for Low-Noise Amplifier Designs," Agilent Application Note 1354 (2000).
[8] Maxim, "Three Methods of Noise Figure Measurement," Application Note 2875 (2003).
[9] NoiseWave, "Noise Frequently Asked Questions," Application Note (2007).
[10] Hewlett Packard, "Noise Figure Primer," Application Note 57 (1965).