Technical Note

HVM Receiver Noise Figure Measurements

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Abstract

In the last few years, low-noise amplifiers (LNA) have become integrated into receiver devices that bring signals from the antenna to analog or digital baseband domains (I and Q). In doing so, it has become more commonplace to test noise figure in this RF-to-baseband configuration. 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. Additionally, considerations for HVM (High-Volume Manufacturing) testing of noise figure are presented.

Introduction

RF-to-baseband front-ends, consisting of a low-noise amplifier (LNA) cascaded with a mixer down-converting RF signals to baseband have become the epitome of RF devices tested in high-volume manufacturing (HVM) today. While the methodologies for measuring noise figure on these devices are the same as those for RF-to-RF devices, the implementations may appear to be somewhat different between bench and ATE (automated test equipment) and between RF-to-RF devices and RF-to-baseband devices.

There are a handful of methods for measuring RF-to-RF noise figure [1]; Y-Factor, Cold Noise, Twice-Power, etc. However, for mainstream RF-to-baseband devices, only two of these are used most often; Y-Factor and Cold Noise. This article focuses on describing noise figure measurements of these RF-to-baseband devices based on practical implementation within the constraints of ATE and production testing (i.e., reduced test time and reduced cost of test).

Noise Figure and Noise Factor

Noise figure is used to determine how much noise is added to a system by a device. In RF-to-baseband receivers, it describes how much added noise comes from both, the amplification *and* the down-conversion and amplification process. Noise figure is related to the fundamental parameter, signal-to-noise ratio (SNR), which is paramount in nearly all electronic applications from audio to the latest generation of wireless consumer devices. High signal-to-noise is essential in most digital communications parameters to achieve low bit error rate (BER) and high carrier-to-noise (C/N) ratio (there is also distortion that adversely impacts BER).

Although the term *noise factor*, *F*, is rarely used, it is the foundation of noise figure. Noise factor is the linear format of signal-to-noise degradation imposed by a device,

$$F = \left. \frac{S_i / N_i}{S_o / N_o} \right|_{T=T_0=290K} \qquad (1)$$

Noise factor is the ratio of input SNR to output SNR at a standardized reference temperature, $T = T_0$, designated by IEEE to be 290K (~17°C) [1]. 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, also called thermal noise. Figure 1 depicts Equation (1), showing this impact of noise on a device. It shows the input power level of a DUT (device under test) with amplification (having a gain, *G*) and the increased noise at the output of the DUT resulting in a decreased signal-to-noise ratio. Note that both input signal and input noise are amplified by the DUT, and are higher at the output of the DUT. However, since the DUT adds noise, the total noise at the output is raised significantly.

The definition of the more commonly used term *noise figure*, represented as *NF*, is related to noise factor by the equation,

$$NF|_{dB} = 10\log_{10}(F). \quad (2)$$

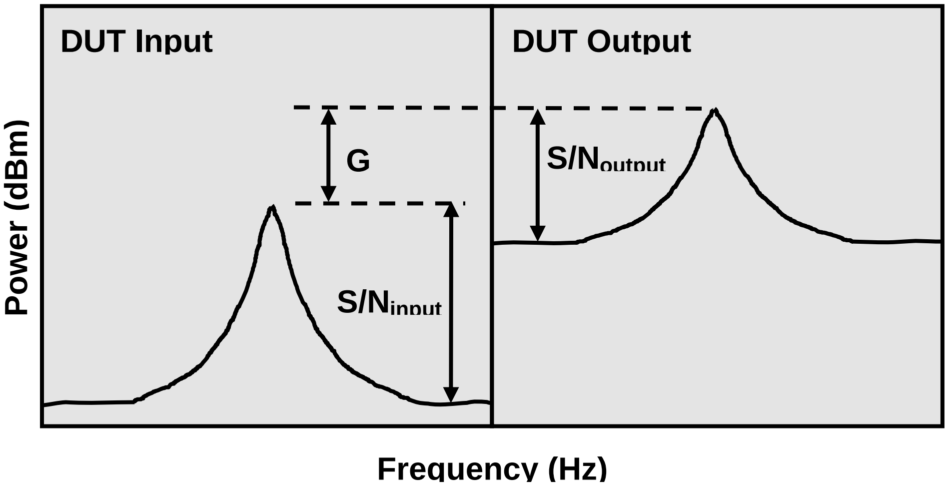

Figure 1. Signal-to-noise degradation of a signal passing through a semiconductor device. The input signal (a) has low peak power and good signal-to-noise properties. The output signal (b) has a higher peak amplitude, but also an increased noise floor, giving overall poor signal-to-noise performance.

Noise Figure Measurement Methods

The Y-Factor Method

The Y-Factor method [2] of measuring noise figure is perhaps the oldest method known. It 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),

$$Y = \frac{P_{hot}}{P_{cold}} \qquad (3)$$

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[1]. 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[2].

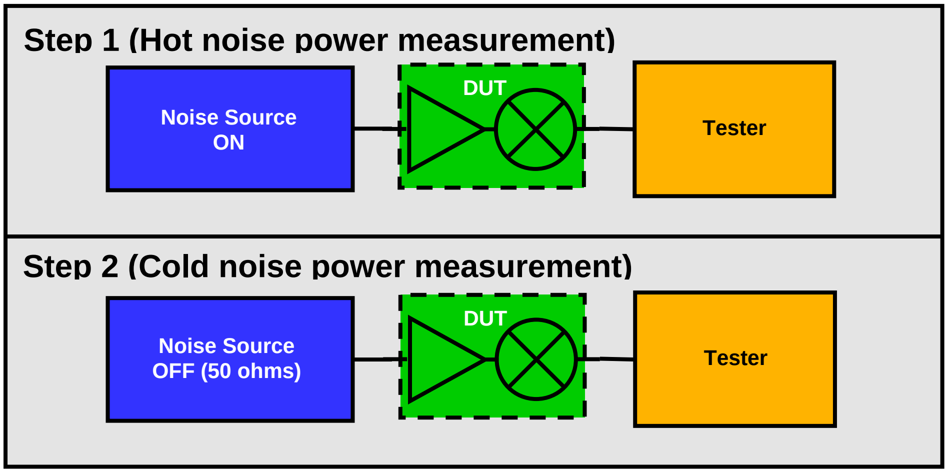

Figure 2. A noise source is applied to the DUT and the resulting output noise powered is measured by the tester. a. The noise source is powered on and provides “hot” noise related to its *ENR*. b. The noise source is powered off, providing a 50-Ohm “cold” termination to the input of the DUT.

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). 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 factor is calculated as,

$$F = \frac{ENR}{(Y-1)} \qquad (4)$$

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[1] 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.

[2] This 50-Ohm impedance is termed *characteristic impedance*, with 50 Ohms being the standard for nearly all RF applications. This work assumes 50 Ohms throughout.

and noise figure (in dB) is,

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

Y is usually much greater than 1 when testing noise figure on RF-to-baseband devices so that the "-1" can be ignored providing a simple equation,

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

Both, Equations (5) and (6) are commonly used for measuring RF-to-baseband 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.

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 factor is calculated as,

$$F = \frac{P_{cold}}{kTBG} \quad (7)$$

or in dB,

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

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 ($1.38\times10^{-23}\mathrm{J}\cdot\mathrm{K}^{-1}\cdot290\mathrm{K}$), converted to logarithmic format, in dBm.

Choosing a Noise Figure Measurement Method

The key differentiating factor of RF-to-baseband devices is that they have a large number of gain states available. This is a result of the combined gain control available, in both the LNA as well as the mixer.

Figure 3 shows a matrix comprised of four different combinations of conditions of gain and noise figure found in RF-to-baseband devices.

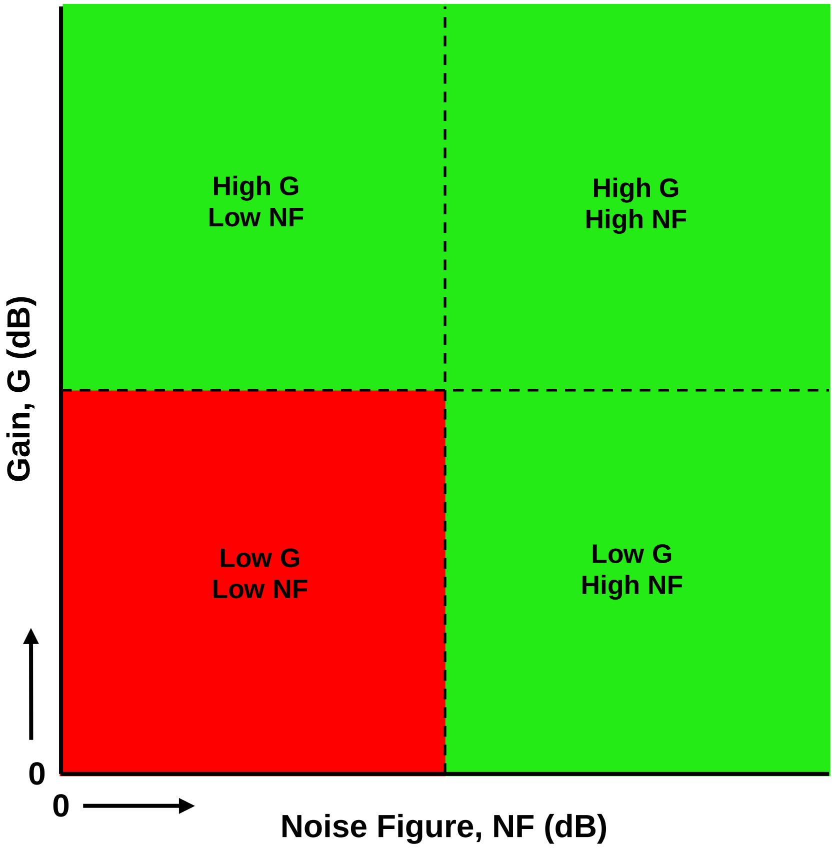

Figure 3. Matrix showing four different combinations of conditions of gain and noise figure found in RF-to-baseband devices.

Device settings having high gain (with low or high noise figure) are the easiest to measure; either method, Y=Factor or Cold Noise, works 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 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*[3].

Both methods become 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

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

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. This is because the noise output from the DUT is significantly greater than the noise of the noise source and *Y* approaches unity (see Equation (5)).

Comparison of Noise Figure Measurement 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 which can be problematic when measuring either very high or very low noise figure values [3] as mentioned in the above section. 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 and hence takes less test time. Overall, the measurement setup and implementation are very simple.

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.

Reference [6] provides details on a study showing that making HVM RF-to-baseband noise figure measurements with either the Cold Noise method or the Y-Factor method using an AWG noise source would be the best choices. Either of these provides a good combination of repeatability, flexibility, measurement correlation and test time. The reason for suggesting the use of the AWG noise source rather than a physical noise diode is because of the wide range of gain and noise figure combinations available in the cascaded RF-to-baseband device (LNA + down-converter). This wide range would require more than one value of *ENR* and this can only be obtained via an adjustable noise source (AWG) with its ability to be played at various power levels (corresponding to different *ENR* values) or multiple physical diode-based noise sources.

Considerations for ATE and Production Noise Figure Measurements

Because noise figure measurements involve the analysis of low-level signals, there are many possible sources of error that can be introduced. Fortunately, for production RF-to-baseband 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. Reference [2] discusses each of these, and how they contribute to inaccuracies and the uncertainty of noise figure measurements in detail.

Averaging of Noise Power Measurements

Because the noise power measurements are at such low power levels, averaging of the power measurements becomes essential. To demonstrate the effect of averaging these power measurements, the Y-Factor method was used to measure noise figure on a DUT (LNA) having an expected noise figure of 1.5dB. For each entry in Table 1, 100 noise figure measurements were made to arrive at the standard deviation (repeatability) shown. In each measurement, the stated combination of measurement averages for the hot and cold noise power measurements were performed.

The repeatability is clearly impacted more by the number of cold averages. This is because cold noise power measurements are closer to the tester noise floor and respond well to higher amounts of averaging than do the hot noise power measurement which is typically well above the tester noise floor.

It is always desirable to have a repeatable measurement made in the least amount of time possible for production testing. Consider, for example, that a test specification has a maximum stated repeatability of 0.11dB. Referring to Table 1, there are three ways to meet those needs (2/4, 4/4, and 8/8). Obviously, the best choice is two hot and four cold averages as it requires the least amount of time (averaging).

No. Avgs. (hot/cold)	**2/2**	**2/4**	**2/8**	**2/16**	**4/4**	**4/8**	**4/16**	**8/8**	**8/16**	**16/16**
Standard Dev. (dB)	0.19	0.11	0.10	0.08	0.11	0.09	0.07	0.11	0.09	0.06

Table 1. Matrix showing how the repeatability of noise figure measurements is highly dependent on the number of averages taken. Each entry is based on 100 measurements.

Measurement Bandwidth

This is another deviation from traditional RF-to-RF noise figure measurements. In most RF-to-RF measurements the traditional bandwidth over which the noise power is measured is 4 MHz. In most RF-to-baseband communications applications, the bandwidth differs from that, consistent with the particular application. For example, in a PCS application, the bandwidth would only need to be around 2 MHz, consistent with its bandwidth of operation.

Variation of Temperature

The actual temperature of the noise source is likely to be different from 290K. For all practical considerations for HVM, this is not a problem. Table 2 shows the variation of T_0 as temperature varies from 280K to 290K (~7degC to 27degC). Notice that the change in T_0 across this 20 degree temperature range is minimal. For LNAs with low to moderate gain and low noise figure, this can be a concern; but for RF-to-baseband receivers with high gain and/or noise figure, this is not of significant concern and is almost always ignored.

The other common assumption is that when Equation (6) is converted to dB, the "1" is dropped from the argument of the log function. Again, for devices with high gain and/or noise figure, making this approximation is rarely problem.

T (Kelvin)	T (Degrees C)	kT (dBm/Hz)	Deviation from kT at 290K (dB)
280	6.85	-174.13	-0.15
282	8.85	-174.10	-0.12
284	10.85	-174.07	-0.09
286	12.85	-174.04	-0.06
288	14.85	-174.01	-0.03
290	16.85	-173.98	0.00
292	18.85	-173.95	0.03
294	20.85	-173.92	0.06
296	22.85	-173.89	0.09
298	24.85	-173.86	0.12
300	26.85	-173.83	0.15

Table 2. Demonstration of effect of varying temperature on thermal noise component, *kT*.

Section 3 of Reference [3] discusses how this deviation from 290K translates to noise figure measurement uncertainty using the Y-Factor method. The findings can also be directly applied to the Cold Noise method.

Noise Figure of the ATE

If the utmost accuracy in making the noise figure measurement is the goal, then acquiring the noise figure of the tester that is measuring the noise power is essential. *This may or may not be necessary, and is often one of the tradeoffs that must be made between accuracy and cost of test.*

The most common way to do this with ATE is to perform a tester noise figure calibration and store the noise figure of the particular paths when the routine tester calibration is performed. This is done either on a weekly, monthly, or as-needed basis, with or without the load board, using a noise source built into the tester. This eliminates the need for load board switches, but also adds a little uncertainty to the measurement, from the uncalibrated region between the calibration plane of the tester and the DUT. Most often, this is not a problem. In RF-to-baseband applications, this calibration can be a little more difficult due to the frequency translation between RF and baseband. For this reason, it is often not performed.

Impedance Matching of DUT to Tester

Any impedance mismatch between the DUT, contactor, load board, and tester results in uncertainty and error in the measurement. This applies equally when making RF-to-baseband noise figure measurements. The noise figure of the DUT is dependent on the input termination, either the noise source or the 50-Ohm termination in the previously mentioned cases. The noise figure of the baseband input of the tester is also a function of the DUT output impedance.

The Future of Noise Figure Measurements

The technological world is constantly driving higher levels of integration within semiconductor devices. Starting from discrete LNA and mixer architecture to modern fully-integrated front-end receivers having minimal external access points, it is becoming more difficult to make noise figure measurements. Today, HVM test is still driven by the device designers who want to relate the final production measurements to what they measure in the basic blocks of the device either on the bench, or in their simulation tools. For now, this is not a problem.

Moving forward, however, designers will have to create new analog test modes within the devices, or noise figure measurements will need to be substituted by sensitivity measurements related to error vector magnitude (EVM) or bit error rate (BER) and packet error rate (PER) (as devices are moving toward RF-to-bits). Today, even though the external package access points are still available, in some technologies the move to make system-level tests like EVM, BER, and PER the primary tests for low-cost devices is already happening. However, it is only in select markets [7]. There is an entire class of low-cost consumer devices including WLAN, Bluetooth, Zigbee, and GPS. They are quite similar in architecture, but of them, only a few technologies such as Bluetooth and Zigbee have made the transition. There are multiple reasons why this may be the case, including:

- Bluetooth and Zigbee are significantly simpler technologies than WLAN and mobile phones.

- Consumers expect a high degree of quality in the connections in WLAN and mobile phones and not quite as much in Bluetooth or Zigbee (it’s not such a problem if a bit/packet is lost in these technologies).

Regardless, for the next few years, analog testing, including noise figure, is going to be around, but the notion of finding a replacement for the bench-relatable noise figure tests may have to be entertained.

Conclusion

Often, tradeoffs must be considered to allow the noise figure measurement to fit into an HVM testing scenario. For example, with the constant drive to reduce cost of test, the measurements need to be done in as short a time as possible. This conflicts with the physics of measuring low-level signals (noise) which inevitably requires averaging, adding execution time to the measurement. In the end, the goal is to get a repeatable production noise figure value that correlates to the bench results as accurately as possible, in as little measurement time as possible.

Overviews of the two most common methods of making RF-to-baseband noise figure measurements were presented. Both of these methods have their place in production testing and either can provide a good combination of repeatability, flexibility, measurement correlation and test time. The Y-Factor method has its roots in the foundation of noise figure meters and analyzers and is therefore a default approach. The Cold Noise method is more production-friendly, requiring only one noise power measurement and ideally reducing test time. A matrix was provided which helps to determine which method is best suited for the given conditions of the DUT.

There are numerous sources of information available in books, web pages, and in application notes, but it is often difficult to separate out the necessary information from the deep physics-based descriptions that are sometimes provided. Verigy recommends the reader to review all of the references in this article, especially [1], [2], and [6]. These describe noise figure in a practical manner, and the information is directly applicable to HVM testing.

References

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