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Make Accurate Sub-1 dB Noise Figure Measurements Part 1: Noise Concepts

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This two-part tutorial describes the theory and practice of noise figure measurement, focusing on the measurement of very low noise figures

One of the most important capabilities of a radio receiver is its ability to reliably detect very weak RF signals. The circuits of a radio receiver inevitably generate electrical noise, which may mask the received signal if the receiver is not properly designed to minimize this noise. The accurate measurement of the receiver's noise performance is of paramount importance in the assessment of its suitability for reliable communications. This concern is compounded by the fact that modern RF systems are increasingly powered by batteries which necessitates the reduction in transmitter output power, which commensurately reduces signal levels at the receiver.

Noise figure (NF) is a figure of merit of RF components that describes their noise performance, and is of particular importance in receiver applications. In addition to the voltage standing wave ratio (VSWR) and the gain of the system itself, the measurement of noise figure is affected by numerous environmental factors such as the ambient temperature and the presence of interference. This article describes practical techniques and methods for accurate noise figure measurement of amplifiers and other 2-port systems having a sub-1 dB noise figure.

First, noise figure concepts are defined and followed by theoretical considerations addressing component loss, impedance mismatch, and temperature. Then, noise figure measurement instrumentation is described and solutions for improving the accuracy of noise figure measurements are provided. Finally, the reference measurement setup used at Skyworks Solutions is described in detail and the characterization of amplifiers over temperature is briefly discussed.

Theoretical Concepts

Noise Factor, Noise Figure, Noise Temperature

As described by Equation 1, the noise factor (F) is defined as the ratio of the input signal to noise ratio to the output signal to noise ratio of the device under test (DUT). S and N respectively refer to signal and noise power.

$$F = \frac{S_i / N_i}{S_o N_o} \qquad (1)$$

The noise factor therefore expresses the degradation in the signal to noise ratio caused by the DUT and is always greater than one. Since power gain is defined as the ratio of the output to the input power (Equation 2),

$$G_A = \frac{S_o}{S_i} \qquad (2)$$

noise factor can also be expressed as in Equation 3.

$$F = \frac{N_o}{N_i G_A} = \frac{N_i G_A + N_{DUT}}{N_i G_A} \qquad (3)$$

is the available thermal noise power at the input of the device and is calculated

$$N_i = kT_{AMB}B \qquad (4)$$

where k is Boltzmann's constant (k = 1.374 × 10^{-23} J/K), T_{AMB} is the ambient temperature in Kelvins and B is the bandwidth in Hertz. N_o

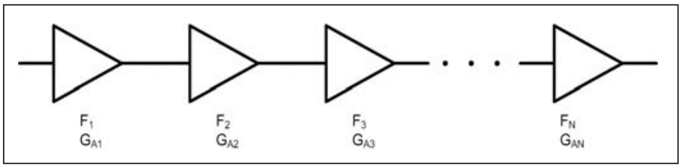

Figure 1 · Cascaded amplifier chain.

is the noise present at the output of the DUT and is composed of the amplified noise available at the input (N_i) and the noise added by the DUT.

Noise figure (NF) is simply the noise factor expressed in decibels (dB) and is calculated using Equation 5.

$$NF = 10\log_{10} F \tag{5}$$

Any noise factor can be expressed as an equivalent noise temperature. Although noise temperature is not commonly used by RF system designers (except for space applications), it is used by most test instruments in their internal calculations and emphasizes the effect of ambient temperature on noise measurements. Noise temperature and noise factor have a linear relationship defined in Equation 6, where T_e is the equivalent noise temperature and T_0 is the reference temperature of 290 K. The noise figure of a DUT is by convention defined at 290 K (16.9 °C or 62.3 °F), regardless of the ambient temperature.

$$T_e = T_0(F-1) \tag{6}$$

Cascaded Noise Figure

It is critical to understand what determines the noise figure of an amplifier chain as it also applies to how the noise figure of an individual component is accurately measured. A noise measurement setup has its own noise figure which must be compensated either by calibration or by applying offsets to the measured results. Given an amplification chain as described in Figure 1 the total noise factor of this cascade is calculated by Equation 7, where F_n and G_{An} refer to the noise factor and gain of the nth stage, respectively.

$$F_{1N} = F_1 + \frac{F_2-1}{G_{A1}} + \frac{F_3-1}{G_{A1}G_{A2}} + \frac{F_4-1}{G_{A1}G_{A2}G_{A3}} + \ldots + \frac{F_N-1}{\prod_{n=1}^{N-1} G_{An}} \tag{7}$$

It can be observed looking at Equation 7 that the noise contribution of each stage to the total noise factor is reduced by the amount of gain of all preceding stages. For that reason one may assume the noise figure of a system is mostly set by the first stage, which is only valid if the gain of the first amplifier is large enough to obscure the noise contribution from the second and so on.

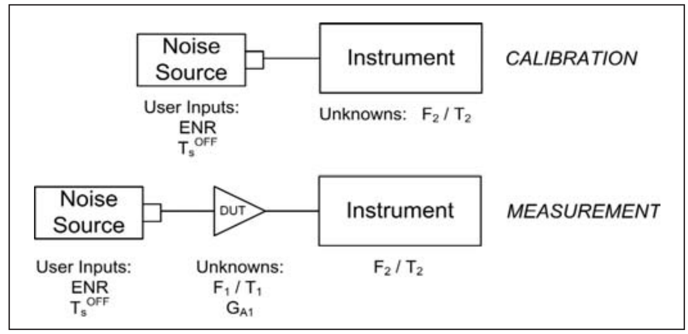

Figure 2 · Block diagram of a noise measurement with the Y-factor method.

Equation 7 is also at the foundation of most noise measurements. The typical noise measurement setup is equivalent to a 2-stage amplification chain in which the DUT can be considered to be the first stage and the instrument the second stage. The noise factor of the DUT, F_1 or T_1, is calculated utilizing Equation 8 or 9 by removing the noise contribution from the instrument, F_2 or T_2, with calibration.

$$F_1 = F_{12} - \left[\frac{F_2-1}{G_{A1}}\right] \tag{8}$$

$$T_1 = T_{12} - \frac{T_2}{G_{A1}} \tag{9}$$

Y-Factor Method

The Y-Factor is how most instruments measure noise figure. It is a simple method that involves two steps: calibration and measurement. The calibration involves connecting a noise source directly at the input of the instrument as shown in Figure 2.

A noise source is a device that emits a known quantity of noise and has 2 states: ON and OFF. During the OFF state, the noise source emits thermal noise corresponding to its ambient or internal temperature. In the ON state, the internal device, normally a diode, is turned ON and a higher quantity of electrical noise is emitted. The offset in noise power between the ON and OFF states is measured during the factory calibration of the noise source and is expressed as an excess noise ratio (ENR) over frequency. The ENR is defined by Equation 10.

$$ENR = \frac{T_s^{ON} - T_s^{OFF}}{T_0} \tag{10}$$

By convention, the ENR table provided with any noise sources is always expressed at $T_s^{OFF} = T_0$. Consequently, the ENR data provided with the noise source is valid only if the noise source physical temperature is 290 K. One may correctly argue T_s^{OFF} may not be 290 K under actual measurement conditions of a DUT as it is highly dependent on the ambient temperature. For that reason, most instruments allow the user to specify the temperature of the noise source so it can correct the provided ENR table thus accounting for any offset from 290 K. It is very important to accurately specify the noise source temperature, especially when measuring sub-1 dB noise figure devices. Figure 3 illustrates the measurement error due to an offset between the specified temperature value and the actual noise source temperature. In this particular case the temperature input from the user is assumed fixed at 290 K while the physical temperature of the noise source is varied. For example, a device having a true noise figure of 0.7 dB at an ambient temperature 6 ºC higher than the noise source temperature input provided by the user will read 0.8 dB on the instrument.

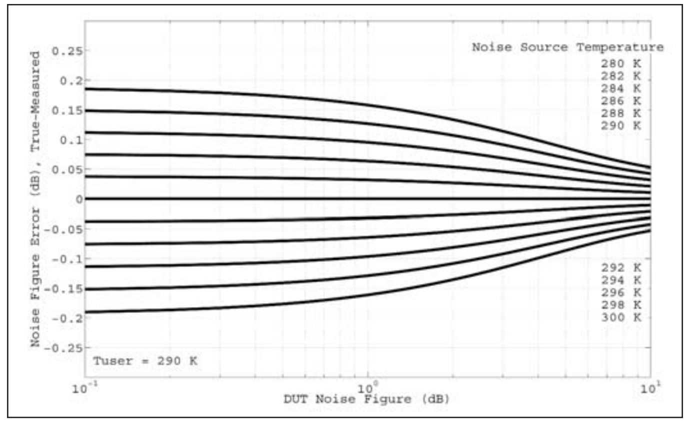

Figure 3 · Noise figure measurement error function of DUT noise figure, at various temperatures. (Assumptions: instrument noise figure is 10 dB, DUT gain is 20 dB, ENR = 6 dB).

During the instrument calibration step, the instrument measures the noise power from the noise source at the ON and OFF state to calculate its own noise temperature T_2, as described by Equation 11. T_s^{OFF} is known from the user's noise source temperature input and T_s^{ON} is calculated from the ENR table. This completes the calibration step.

$$Y_2 = \frac{N_2^{ON}}{N_2^{OFF}} = \frac{T_s^{ON} + T_2}{T_s^{OFF} + T_2} \qquad (11)$$

The second step consists of inserting the DUT between the noise source and the instrument. The instrument then repeats the same measurement while switching the noise source between the ON and OFF states as described in Equation 12. Then, it calculates T_{12}.

$$Y_{12} = \frac{N_{12}^{ON}}{N_{12}^{OFF}} = \frac{T_s^{ON} + T_{12}}{T_s^{OFF} + T_{12}} \qquad (12)$$

As can be observed from Equation 9, the only parameter missing to calculate the noise temperature of the DUT is its gain (G_1) which is readily available from the measured data as described by Equation 13.

$$G_1 = \frac{N_{12}^{ON} - N_{12}^{OFF}}{N_2^{ON} - N_2^{OFF}} \qquad (13)$$

Proper Calibration

Noise measurements are not always well understood which may lead to erroneous calibrations and therefore erroneous measurement results. When sub-1 dB noise figure measurements are performed, subtle calibration errors may be uncovered that would otherwise be barely perceptible with noisier devices. The most critical rule to remember is to never include components located before the DUT in the calibration loop unless the ENR table is corrected. The purpose of the calibration is solely to measure the noise contribution of the instrument so it can be removed from the total cascaded noise figure, thus allowing the noise figure of the DUT to be isolated. Input losses that cannot be avoided should always be accounted for during post-processing of the measurement. Output losses can either be accounted for in post-processing or during calibration. In the latter case, the noise source is connected to the instrument through other components required at the output of the DUT while the calibration is performed. The contribution from these components is then absorbed by the instrument during calibration. In this case, temperature adjustments are no longer possible which is typically not a problem as will later be demonstrated. It is also imperative the added components remain at the output of the DUT during measurement.

Accounting for Losses

In a laboratory environment, a DUT may not be easily accessible and may require connectors, cables, attenuators, etc., to be measured with a noise measurement setup. These elements all create combined reflective and dissipative losses affecting the noise figure measurement by adding attenuation which may add directly to the noise figure, reduce gain, or add noise to the system. These losses are typically left in the setup because they are physically or mechanically required to perform the measurement. It is therefore necessary to remove their effects in a post processing step. Most noise figure measuring instruments have built-in menus and functions that allow corrections for losses automatically, based on user input.

Figure 4 shows a typical noise measurement setup in which the DUT is enclosed between lossy elements. $L_{IN/OUT}$ and T_L respectively represent the loss and the temperature of the element. $L_{IN/OUT}$ is calculated from

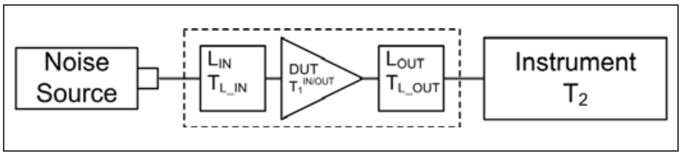

Figure 4 · Noise measurement setup including losses.

the loss in decibel using equation 14.

$$L_{IN/OUT} = 10^{L_{IN/OUT\_dB}/10} \qquad (14)$$

Input Losses

Equation 15 describes the noise temperature of the DUT once compensated for input losses, defined as T_1^{IN}. Note the second term of the equation only applies to dissipative losses and should be omitted if the loss is purely reflective.

$$T_1^{IN} = \frac{T_1}{L_{IN}} - \frac{T_{L\_IN}\left(L_{IN} - 1\right)}{L_{IN}} \qquad (15)$$

A dissipative element is also a source of noise on the basis of its physical temperature as illustrated by the T_{L_IN} term in Equation 15. It is commonly assumed the effect on noise figure of an attenuator placed at the input of the DUT is equal to its the insertion loss (L_{IN}). This assumption is correct only at an ambient temperature of 290 K as described by Equation 16.

$$F_1^{IN}\Big|_{T_{L\_IN}=T_0} = 1 + \frac{T_1^{IN}\Big|_{T_{L\_IN}=T_0}}{T_0} = \frac{F_1}{L_{IN}} \qquad (16)$$

Figure 5 illustrates the combined effect of dissipative input loss and temperature on the corrected noise figure of the DUT for a 1 dB noise figure measurement. As can be seen, if $T_{L\_IN} = T_0$, the correction in dB is simply the $NF_{1\_dB} - L_{IN\_dB}$. In the case of higher loss, temperature may have a non-negligible contribution to the measurement and must be taken into account.

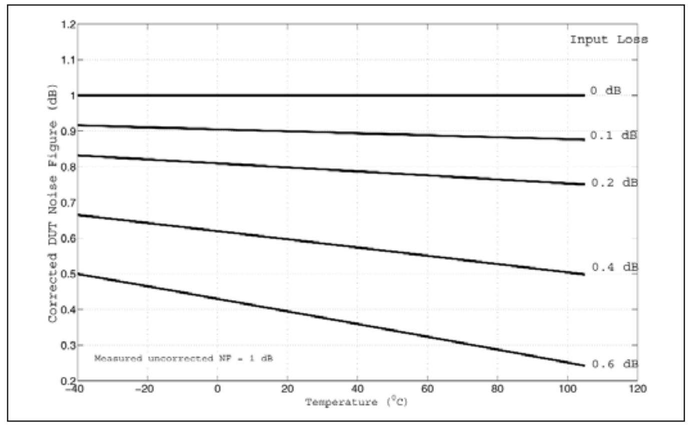

Figure 5 · Corrected noise figure function of the loss at the input and temperature. (Assumption: the measured uncorrected noise figure is constant at 1 dB).

Output Losses

Reasonably small output losses are less troublesome than input losses in typical noise measurement setups. In addition, their effect on the measurement can easily be calibrated out as was explained earlier.

There are two reasons that explain the lower sensitivity of noise figure measurements to output losses: the noise figure of the instrument and gain of the device. As described in Equations 17 and 18, the correction for output loss is applied to the noise temperature of the instrument, T_2, which can be high, especially for spectrum analyzers with a noise figure measurement personality. This means most loss at the output will be small compared to

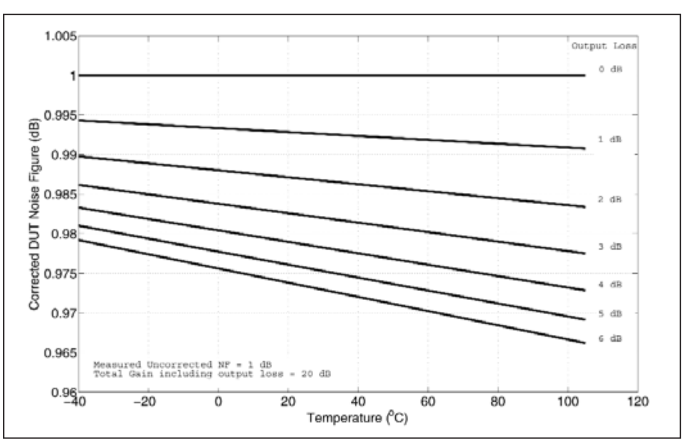

Figure 6 · Corrected noise figure function of the loss at the output and temperature. (Assumptions: instrument noise figure is 10 dB, the total cascaded gain is 20 dB and the total cascaded noise figure measured is 1dB).

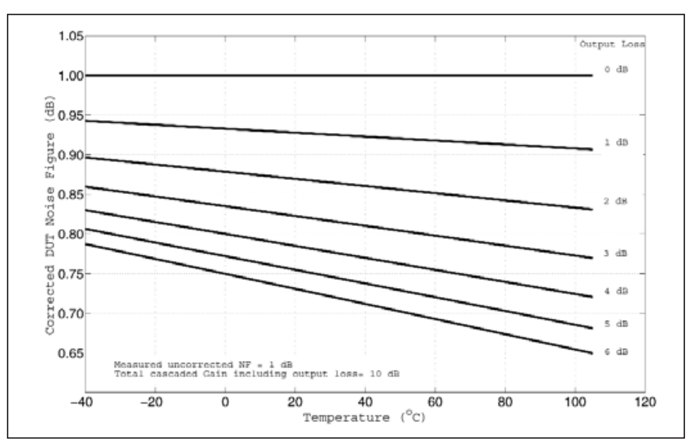

Figure 7 · Corrected noise figure function of the loss at the output and temperature. (Assumptions: instrument noise figure is 10 dB, the total cascaded gain is 10 dB and the total cascaded noise figure measured is 1dB).

the instrument's own noise figure unless a large value attenuator is used. As an example, the Agilent MXA N9020 with preamplifier has a noise figure of 10 dB at 2 GHz. The gain of the DUT reduces the sensitivity further by making corrections for output loss even less perceptible. T_2^{OUT} is the noise temperature of the instrument corrected for the loss at the output of the DUT that was *not* present during calibration. T_1^{OUT} is the corrected noise temperature of the DUT compensated for output loss.

$$T_2^{OUT} = T_2 L_{OUT} + T_{L\_OUT}\left(L_{OUT} - 1\right) \quad (17)$$

$$T_1^{OUT} = T_{12} - \frac{T_2^{OUT}}{G_{AI}} \quad (18)$$

Figure 6 illustrates the effect of dissipative output losses on the measured noise figure of the DUT when the total cascaded gain is 20 dB including the output loss. As can be seen, the measured noise figure is less sensitive to output loss and the variation of the correction over temperature is negligible. Figure 7 illustrates the increased sensitivity of the measurement to output loss and temperature when the same calculation is performed with a total cascaded gain of only 10 dB.

This article continues next month, with Part 2 covering noise figure measurement methods.

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