NF (Noise Figure)

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Noise can be composed of both environmental deterministic noise (e.g. spurious RF) and random thermal noise. This note focuses on random noise and its measurement. A perfect electronic device would perform its function and add no noise that wasn't presented at its input. Practical devices add noise and therefore reduce the signal-to-noise ratio of their system. Noise factor is the ratio of noise power out to noise power in (output referred by gain). And noise figure is noise factor in dB units. Of particular importance are devices in the early stages of amplified systems since their noise will be amplified in subsequent stages.

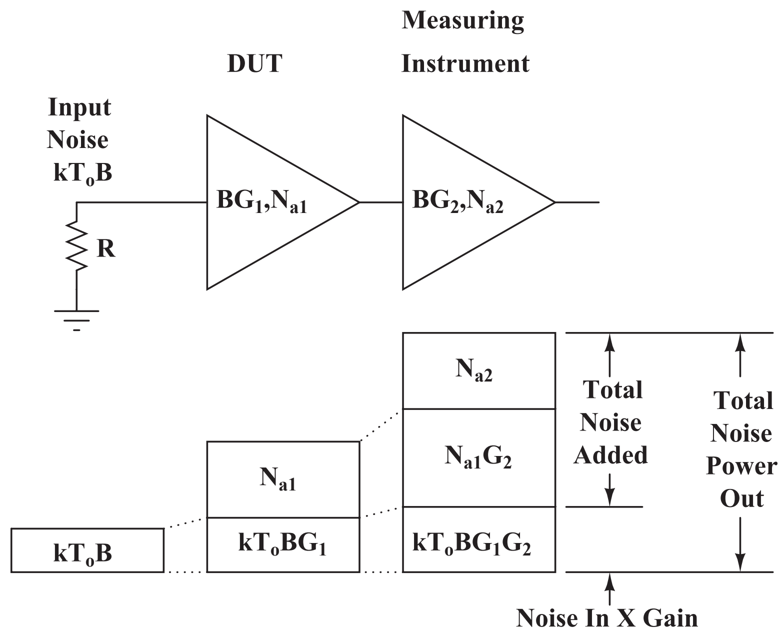

Figure 1: Multi Stage Noise

Figure 1 shows the noise increase in a cascaded system. Input noise is usually thermal noise portrayed as Brownian motion. Thermal noise power is defined as kT_oB where k is Boltzmann's constant, T_o is Kelvin temperature and B is bandwidth in Hz. The T_o standard has been set at 290 ^oK (17 ^oC) as the average earth temperature. Thermal input noise power at 290 ^oK would be:

$$P_{NIN} = \left(1.38 * 10^{-23} W / Hz^o K\right) * \left(1000 mW / W\right) * \left(290^o K\right) = -174 dBm / Hz \qquad (1)$$

This is thermal noise floor normalized to 1 Hz bandwidth and presented to the input of our system. In stage 1 the input noise is amplified and in addition some noise (N_{a1}) is added on top of that. Note that stage 2 might be our measuring instrument and it too would add some noise to the overall system. Let's first consider the case where our measuring device noise contribution is significantly less than the DUT. For these conditions direct measurement methods are effective.

Direct Method

Noise factor F is noise-out divided by gain times noise-in:

$$F = \frac{P_{NOUT}}{kT_0 B G_1} \tag{2a}$$

Noise factor F is in the linear realm and noise figure NF in the logarithmic realm.

$$NF = 10\log_{10} F \tag{2b}$$

$$NF = P_{NOUT} - \left(10\log_{10} B + G_1 - 174\right) \tag{2c}$$

P_{NOUT} is measured with either a sampling digitizer or spectrum analyzer. The sampling digitizer captures voltage samples which are converted to frequency domain power bins. Since random noise is uncorrelated, total noise power is the root-sum-square of the frequency power bins. The gain of the DUT is measured over the target bandwidth. And the target bandwidth is applied to equation 2c to yield NF. For setup the DUT input is terminated in it's characteristic impedance and the DUT output is connected/terminated to the P_{NOUT} measurement instrument and terminated in it's characteristic impedance. Noise figure should be measured with a bandwidth as wide as possible but narrower than the DUT.

If the sum of DUT gain and expected noise figure is below the measuring instrument noise figure (10 to 20 dB), direct methods won't work. Instead one can use a calibrated noise source switched on and off to measure the noise slope of the DUT. The noise source can be used to stimulate the DUT much higher than the -174 dBm floor.

Y Factor Method

The calibrated noise source is usually a diode that is reverse avalanche biased to generate noise. It has calibrated measurements of ENR (excess noise ratio) in terms of equivalent noise temperatures on (T_h) and off (T_c). ENR is the difference between T_h and T_c divided by 290 ^oK. T_c can be assumed to be 290 ^oK in most cases where the noise source is near or forced to 290 ^oK (17 ^oC). With the noise source connected to the DUT, the output power is measured with noise source on (N_2) and noise source off (N_1). Y factor is defined as the ratio N_2/N_1. A straight line slope is a fundamental characteristic noise power out vs temperature.

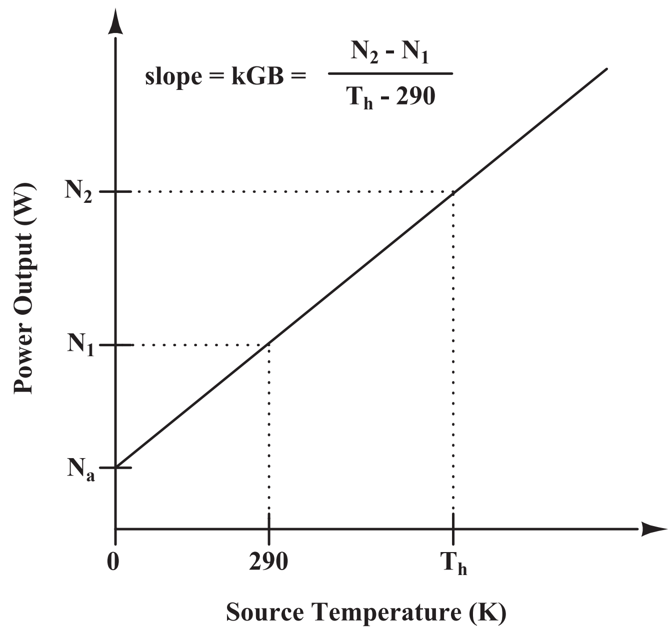

Figure 2: Noise Power Out VS Temperature

At absolute zero the noise power out consists solely of DUT added noise N_a. We can employ the published ENR and measured N_2 and N_1 to calculate NF. By using the noise slope the measurement is independent of Gain and Bandwidth.

$$ENR = \frac{T_h - 290}{290} \quad ; \quad Y = \frac{N_2}{N_1} \quad \therefore \quad Y\text{-}1 = \frac{N_2 - N_1}{N_1}$$

$$\text{slope:} \quad kGB = \frac{N_2 - N_1}{T_h - 290} \quad ; \quad F = \frac{N_2}{T_h kGB} = \frac{N_1}{290\ kGB}$$

$$F = \frac{N_1}{290}\left(\frac{T_h - 290}{N_2 - N_1}\right) = \left(\frac{T_h - 290}{290}\right)\left(\frac{N_1}{N_2 - N_1}\right) = \frac{ENR}{Y\text{-}1}$$

When ENR and Y are in dB terms:

$$NF = 10\log_{10}\left(\frac{10^{ENR/10}}{10^{Y/10} - 1}\right) \tag{3a}$$

If the DUT noise figure is much higher than the ENR the DUT noise tends to mask the noise source. The Y-factor will be very close to 1 and measurement errors will dominate. The noise source should NOT be used when DUT NF is more than 10 dB above the ENR of the noise source. If the noise source is not near 290 ^oK the ENR may be modified as ENR*T_c/290.

There is one more caveat. The Y-factor method determines the cascaded system noise factor as shown in Figure 1. The DUT noise factor can be calculated using the cascade noise equation (linear realm):

$$F_{SYS} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots \qquad (3b)$$

Passive lossy stages such as LCR elements have a noise figure equal to the loss and gain equal to the inverse of loss. In order for Y factor to be effective the overall system should have a gain of at least 5 to 10 dB. This can be effected by adding a low noise amplifier as a first stage. The measurement instrument noise figure can be determined by direct connection of the noise source to the instrument. The DUT Gain measurement has likely been made previously.

Significant measurement errors can be introduced with instrument uncertainties, DUT match uncertainties and environmental contaminants (e.g. Spurious RF).

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