Microwave Low Noise Amplifiers—*Part 2*

In the first installment of Microwave LNAs (January 2004 *QST*) we explored circuits and construction. While writing this installment, I discovered that it would take several issues to do at least a minimal job of explaining noise and system performance. So, please forgive me in advance for stretching the topic over so much time.

In order to decide whether we should spend the extra money and effort to obtain that last tenth of a decibel of noise figure, we will look at what these numbers mean and what is happening in front of the LNA. I wish to also mention that the equations and tricky concepts in this and subsequent columns might seem daunting. This column gets the most positive feedback when it bends toward the technical, and although some of this may be new to you, it is probably no more complicated than problems on your license exam—so here goes.

Gain and dB

The important characteristics of LNAs are gain and noise figure. In order to be useful, LNAs must amplify at the frequency of interest, and not oscillate. The gain, usually measured in the logarithmic scale of dB, is a measure of the output power relative to the input power. We want our LNAs to have sufficient gain to overcome losses that come after the LNA, but not so much gain that its components will distort the signal or overload the subsequent stages. Our ability to copy a signal compares the noise to the signal, hopefully ending up with more signal than noise. The signal-to-noise ratio can be expressed as a linear factor or in decibels.

Noise Figure and Temperature

The noise figure is also expressed as dB, but relates to the power radiated by objects at a "standard temperature," which is usually 290 kelvins (the Kelvin scale starts at absolute zero) or just about 62°F. Some texts will use 293 or 295 K because it is closer to room temperature, but the IRE (and therefore the IEEE) adopted standard is 290 K.[1] The results are nearly the same. It is helpful to understand the concept of noise figure and temperature, so here is a brief explanation.[2]

Every object in the universe emits broadband electromagnetic radiation. Both the amount of that radiation emitted, and the upper frequency at which it stops, increase with temperature. This is a property of physics—as described by Planck's radiation law. At all temperatures that we deal with, and frequencies below a few hundred GHz, the power of the emitted radiation is directly proportional to the temperature. (Some objects are more reflective than others, and just like a mirror reflects the scene around it, perfectly reflective objects have an apparent temperature of the objects they reflect.) We can conduct an experiment with an enclosure, lined with good absorber (which because it is non-reflective, is also good "emitter") and kept at 290 K. Into this enclosure we place an antenna and measure the power at the antenna terminals. Regardless of the frequency or size of the antenna, we would measure –173.98 dBm ($10^{-17.4}$ mW) of power over each Hz of bandwidth. Temperature is a linear measure of power, so twice as many degrees represent twice the power.

It turns out that a matched resistor (usually 50 Ω) also at 290 K, if substituted for our antenna and room will produce exactly the same power level. This power level is the standard-temperature power that is referenced when we describe the noise figure of an LNA.

Noise Figure Example

When an LNA, with its input properly terminated to a resistor at 290 K produces exactly twice as much output noise as it would if it were only amplifying the input noise from the resistor, we say that the LNA has a noise figure of 3 dB. We would also say that it has a *noise factor* of 2 (noise factor is the linear version of noise figure). To avoid confusion, the rest of this column will use noise figure (not noise factor) because it is the most common way of expressing LNA noise. In the next column, noise factor will reappear.

The output we measure in this case has exactly twice the power than we would expect if the amplifier were contributing no noise itself, and a linear factor of two is 3 dB (10 × log(2) = 3). In this situation, the LNA output has half of its power coming from the resistor and half from the noise generated in the amplifier. Although the amplifier-generated noise might come from places other than the input circuit, we treat the LNA as though all the internally generated noise at its output were coming from its input circuit and amplified with the same gain as the input signal. This way the gain and the noise are separate quantities, both relating the output to the input.

If there were no noise being contributed by the amplifier, then the output would simply be the terminating resistor

The Decibel...

Recall that a decibel is one tenth of a bel, and that one bel represents a power ratio of 10. So, an amplifier with a gain of 20 dB would have an output that is 100 times the power of the input (10 raised to the 2.0 power is 100). In another example, a linear gain of 50 would be about 17 dB (because 10 times log(50) is 17). dB is a power ratio, so for amplifiers we measure the ratio between the output and input power as the gain, and for signal-to-noise is the ratio between the signal and the noise. The formulas are:

$$\text{Gain}_{dB} = 10 \cdot \log\left(\frac{P_{out}}{P_{in}}\right)$$

$$\text{Signal-to-noise}_{dB} = 10 \cdot \log\left(\frac{P_{signal}}{P_{noise}}\right)$$

$$\text{Gain}_{linear} = 10^{\frac{\text{Gain}_{dB}}{10}}$$

$$\text{Signal-to-noise}_{linear} = 10^{\frac{\text{Signal-to-noise}_{dB}}{10}}$$

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power (times the amplifier gain) times the linear factor of 1. We would characterize this fictitious (perfect) LNA as having a noise figure of 0 dB. This is 0 dB because the output power is a linear factor of 1 times the input resistor power (times the gain), and 10 × log(1) = 0.

Noise Temperature Example

Another way of expressing the noise of an LNA is by its apparent *noise temperature*. Here, the LNA is characterized by the equivalent temperature (in kelvins) that a properly matched input resistor (or enclosed antenna) would have to be set to in order to produce the same power if the LNA had no internally generated noise at all. In the case of the 3 dB noise figure LNA, we would say that it has a noise temperature of 290 K. If a (perfect) LNA had no noise contribution, its noise temperature would be 0 K. Just as with noise figure, we pretend that all the LNA generated noise is present at its input and amplified along with the input signal and noise.

Amateur radio LNAs and microwave receivers are most often characterized in dB noise figure, whereas satellite LNAs and systems are most often characterized in noise temperature. There are exceptions, and some are characterized both ways. As you will see below, there are times when it is more convenient to think of LNA noise one way than the other. In fact, to comprehend and calculate realistic situations, both measures are sometimes used. See the equations and Table 1 to convert between these measures.

Table 1
Some Noise Figures and Equivalent Noise Temperatures

Noise Figure (dB)	*Noise Temperature (K)*
0	0
0.3	21
0.6	43
1	75
1.3	100
1.6	129
2	170
2.3	202
2.6	238
3	290

You can easily convert between noise figure and noise temperature. Noise figure is a logarithmic measure, in decibels. Noise temperature is a linear measure, in kelvins. To go from noise figure to temperature use this formula:

$$T[\text{Kelvin}] = 290 \times 10^{\frac{nf[dB]}{10}} - 290$$

To go from temperature to noise figure, use this formula:

$$nf[dB] = 10 \times \log\left(\frac{T[\text{Kelvin}] + 290}{290}\right)$$

Are LNAs Needed?

So, just when are LNAs useful? They can be expensive, especially at the highest frequencies and lowest noise figures. The only way to really understand the value of an LNA is to put one into service and measure the performance before and after. Short of this, it is often very instructive (and cost effective) to analyze the system, and predict performance before spending money or effort.

Just how does the installation of an LNA in your system improve performance? Of all the things that bear on the analysis, two are probably the most important. The first is the temperature of the area where the antenna is pointed. The second is loss—and the most important losses are those between the antenna and LNA, and from the LNA output to the next electronic stage, usually a mixer or additional amplifier. The next installment of this column will deal with losses. For simplicity, let's assume that there is sufficient gain in the LNA to overcome performance weaknesses in subsequent receiver stages, but not too much as to introduce distortion, and concentrate on understanding LNA noise effects.

The Temperature your Antenna "Sees"

Most of us who are eking out another contact on the microwave bands communicate terrestrially, that is, point our antennas toward other places on Earth. Some of us are not, because we are pointing into space at active or passive satellites (e.g. OSCAR or the Moon). First, let's examine the situation where the antenna is pointed into space. The majority of the beamwidth of the antenna is subtended by empty space. Except when the antenna is pointing at the energetic galactic center or the Sun, the noise (temperature) from space is quite low, and because the antenna is pointed up, the beam penetrates only a few miles of atmosphere.

The temperature a perfect antenna sees will be under 8 K from 1 GHz to 10 GHz when pointing at angles from straight up to 60° down from zenith, and rises as the beam approaches the horizon and encounters more atmosphere. Real antennas, because they receive some energy from sidelobes, will see slightly higher temperatures of about 15 K. The signal from the satellite, even if very weak may still be stronger than the extremely low thermal noise entering the antenna. This is important to satellite broadcasting. A reasonably sized satellite-borne transmitter provides sufficient energy to cover most of a continent because the background noise experienced by the up-pointing receivers is so low. Mass production of these receivers is a contributing factor to the availability of inexpensive components that achieve low noise in the microwave region.

An LNA that adds minimum noise will be very useful in amplifying these weak signals, keeping the signal stronger than the combination of noise from the antenna and from the LNA. In fact, the lower the LNA noise, the better, until the LNA's input noise is at or below the noise that the antenna sees. The very best practical LNAs in the 1 to 10 GHz region have noise temperatures of about 20 K, and therefore generate at least slightly more noise than a space-pointed antenna receives.

Compare the space situation to a terrestrial one. Now we are pointing at the horizon, so half of the beamwidth is occupied by warm Earth and the other half by dozens to hundreds of miles of atmosphere before it "sees" cold space. The noise power at the antenna will vary with frequency, because the emissions of the atmosphere also vary with frequency. The minimum total, if the atmosphere were completely transparent, would be 150 K, but in temperate climates the noise power would typically be equivalent to over 200 K. If it is a warm and moist day, it will approach 290 K, perhaps even be exactly that number. The signal must be stronger than this background thermal noise in order to be heard—even with a perfect LNA that introduces no noise at all. Any additional electronic noise will further mask the signal.

Next Time

In the next few columns we will continue our LNA understanding by looking at the loss in front of the LNA (between the antenna feed and the amplifier), and review the complete microwave receiver to see where performance problems might exist, including a calculation of total noise figure.

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Notes

[1]"Noise Figures of Radio Receivers," *Proc of the IRE*, July 1944, pp 419-422, by H. Friss, is the definitive paper for those interested in the scientific and mathematical relationships that establish noise figure and factor measurements.

[2]Agilent Technologies, Inc, has an excellent application note on noise figure measurement. If you want a copy, go to **www.agilent.com/** and enter "AN 57-1" into the search box.