Noise in Microwave Receivers

In the first installment of Microwave Low Noise Amplifiers (January 2004 *QST*), we explored circuits and construction. In the second installment (March 2004 *QST*), we continued with an understanding of noise, and ran through some examples and formulas. Now it is time to look at an entire receive system to determine our ability to dig signals out of the noise.

Review

In review, let's recall the units and measures that we employ for gain and noise. These can be logarithmic or linear, and because formulas and our understanding can work easier with a particular choice, it is helpful to be able to convert between them.

Linear measures express the relationship between units as direct multiples. For instance, if we have 200 mW going into an amplifier, and a linear gain factor of 4, then the output is expected to be 800 mW. If we have a linear signal to noise ratio of 20, we expect the signal to have twenty times the power of the noise (in the bandwidth). If we have a noise temperature of 1000 kelvins (K) and add a noise power

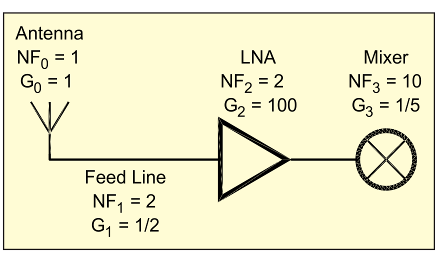

Figure 1—A simple example of a receiver front end.

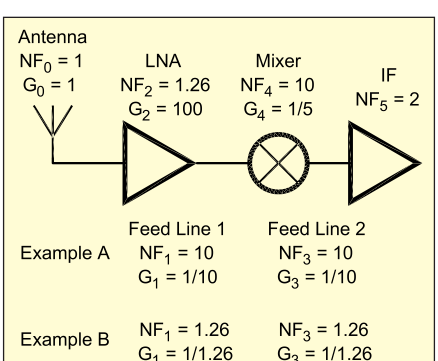

Figure 2—LNA placement (A) in shack and (B) at top of tower.

Noise Factor

We use *noise factor* (NF) rather than *noise figure* (nf) in this calculation, and can convert to any units when done. If noise is expressed in temperature or noise figure, it must be converted to noise factor for each component. The formula for cascaded noise factor is:

$$CNF_1 = NF_0 + \frac{NF_1 - 1}{G_0} \quad CNF_2 = CNF_1 + \frac{NF_2 - 1}{G_0 G_1} \quad CNF_3 = CNF_2 + \frac{NF_3 - 1}{G_0 G_1 G_2}$$

and so forth—or for an entire system:

$$CNFsystem = NF_0 + \frac{NF_1 - 1}{G_0} + \frac{NF2_1 - 1}{G_0 G_1} + \ldots$$

Where CNFx is the cascaded noise factor at the output of element x, NFx is the noise factor of the individual element at stage x, and Gx is the linear gain of element x. Losses are expressed as fractional values for linear gain and the noise factor for an attenuator is equal to the inverse of the fractional gain, for example a 3 dB attenuator has a gain of ½ and a noise factor of

$$\frac{1}{1/2} \text{ or } 2.$$

Refer to Figure 1 for our first example. Our first element (subscript of zero) is the antenna. Assuming it has no significant resistive losses, it has a linear noise factor of 1 (no noise) so NF_0 is therefore 1, and no loss or gain, so its linear gain is 1. The next element is the feed line. Its loss is a linear gain fraction, for example ½ for 3 dB of loss, and the noise factor of an attenuator is the inverse of the gain, or in this case 2. Applying the equation, we get a CNF_1 of 2. We can put our LNA next. Let's assume 20 dB of gain (linear gain factor of 100) and a noise factor of 2 (same as a noise figure of 3 dB or temperature of 290 K). Applying these numbers we get a CNF_2 of 4. To convert to noise figure, we take 10 log(4) = 6 dB noise figure at the output of the LNA. Just as derived above, the 3 dB of feed-line loss directly added to the 3 dB of LNA noise figure to make a 6 dB system. When you take the next step, where typically a feed line and/or a mixer follows the LNA, you will see that quite a bit of loss can be tolerated without sacrificing much system noise figure. It is the gain of the LNA that overcomes the effects of the subsequent loss.

If you do some rough calculations you can see that a typical hilltop system with feed-line loss below 1 dB, an LNA with about 20 dB of gain and a noise figure of better than 1dB, driving a mixer with a (conversion) loss of 7 dB and a noise figure below 10 dB, can result in a complete receiver that has a noise figure below 2.5 dB.

Let's examine two home station examples. As shown in Figure 2, example A, we have an antenna mounted at some distance from the receiver. It is not uncommon to have 10 dB of tower-to-shack cable loss at microwave frequencies, and we use that figure for this example. Adding an excellent LNA with a 1 dB noise figure and 20 dB of gain at the end of such a lossy feed line, followed a 1 dB loss in front of the example mixer and first IF stage, results in a total system noise figure of about 11.5 dB. You are invited to do the calculation yourself. On bands below 47 GHz, an 11 dB system noise figure is considered very poor performance.

Now, as shown in example B of Figure 2, let's move the LNA near the antenna, and assume that cabling and TR relay introduce 1 dB of loss between the antenna and LNA. Using the same cable with 10 dB of loss from the tower to the receiver, the equations show that the resulting system noise figure is about 5 dB. This is a much better result than the previous example, but has the added complexity of a mast mounted LNA and remote TR switching and sequencing. Most microwavers with home stations remotely mount LNAs and TR relays near the antenna in order to overcome the effect of feed-line loss. Even high performance portable hilltopping stations are designed with the lowest possible loss in the TR switching and feed lines in order to get the best performance from the receiver.

My thanks go to Dick Knadle, K2RIW, for his help in reviewing this column. Dick has been a significant technical contributor to the VHF and above amateur community for a number of years.

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equivalent to 2000 K, then the result is a noise power equivalent of 3000 K. If we have a noise factor of 2, and double it, we will end up with a noise factor of 4. All of these are linear measures.

Logarithmic measures are expressed in decibels, where a decibel is 10 times the logarithm of the linear measure. In our case of an amplifier with a gain factor of 4, we would say that it has 10 log(4) or about 6 dB of gain. In our case of a linear signal-to-noise ratio of 20, we would have a 13 dB signal-to-noise ratio. Going from 1000 K to 3000 K is the equivalent of going from a noise figure (referenced to the standard 290 K) of 6.48 dB to a noise figure of 10.54 dB, or a 4.06 dB worsening of noise figure. A noise factor of 2 is a noise figure of 10 log(2) or about 3 dB, and a noise factor of 4 is about a 6 dB noise figure. If any of these are puzzling, please review the formulas in the March 2004 column.

What do we Want our Receivers to do for Us?

Receivers are meant to receive the signal of interest and minimize the reception of signals and noise that are not the signal of interest. Interference rejection, selectivity, and distortion are important parts of this process, but are not considered in this column. We are, however, interested in minimizing noise while providing sufficient gain to hear the weakest of signals. And so, we focus on gain and noise. Recall that the opposite of gain is loss, and is often expressed as a negative logarithm (for example, –3 dB) or a fractional linear measure (for example, ½).

The noise performance of a receiver can be treated as a cascade of its gain (and loss) elements, each with its own noise contribution. Recall that the formulations for the noise figure, noise factor, and noise temperature of an amplifier all are devised so as to make the amplifier appear to have perfect gain with the electronic noise contribution of the amplifier injected at its input terminals. Although this model is not usually correct, it does not matter because the amplifier or other element of a system is treated as a "black-box"—meaning that we do not have to understand its inner workings to fully comprehend its effects in the system. Its external behavior is completely sufficient for this type of analysis. We can also apply the same reasoning to other elements of the receiver that are not amplifiers, such as a mixer or attenuator.

Loss Between the Antenna and Low Noise Amplifier

Any loss between the feed and the LNA adds to the noise figure of the system. Unfortunately, the amount of this loss is often simplified. As you will see, in cases where the background noise power entering the antenna is 290 K, the degraded noise figure is exactly equal to the loss, but for other cases it can be quite a bit more. In the following example, let's consider a signal that is 3 dB above the thermal noise at the antenna terminals (in the given bandwidth). Noise temperature is a measure of power, so we can say that the *equivalent temperature* of the signal is twice the thermal background, or in this case 2 × 290 = 580 K.

Just what affect does loss in front of our LNA have on performance? We know that the loss elements (such as the antenna feed, any coax or waveguide, and the TR relay) provide some measurable attenuation of the signal. This attenuation applies equally to the background noise and the signal. The attenuator also provides noise of its own, and is in proportion to the amount of attenuation and the physical temperature of the loss elements. Because amateurs do not have the means to cryogenically cool their feed lines, let's assume that the loss elements are at standard temperature.

The amount of noise added by the lossy components is one minus the gain factor times the physical temperature (in kelvins). Remember that a loss is a fractional gain. So, if we have 3 dB of loss, we would have a gain of –3 dB or a linear factor of ½. Because 1–½ is ½, the added noise is ½ of 290 K or 145 K.

Let's try an example. If we have a background noise of 290 K and a signal equivalent to 580 K, then the signal-to-noise ratio entering our antenna (over the given bandwidth) is a linear factor of 580/290 = 2 (or 3 dB). We know that the feed line loses 3 dB, or a linear gain of ½, so the background power drops form 290 to 145 K and the signal drops from 580 to 290 K at the output of the feed line. The feed line adds 145 K of noise, so now the signal is at 290 K and the noise is at 145+145 = 290 K. The signal-to-noise ratio has become a linear factor of 290/290 = 1, or 0 dB (signal power equal to noise power) or a degradation of 3 dB from its original. In this case the signal-to-noise ratio has dropped by exactly the same amount as the loss. So, in terrestrial examples it is convenient to calculate degradation of front-end noise by exactly the loss between the feed line and the LNA.

Now let's try the same thing, but with a space-pointed antenna. Here the background thermal noise into the antenna might be as low as 15 K. Let's assume that the signal from the satellite (in the given bandwidth) 3 dB stronger than the noise, or 30 K equivalent. Our 3 dB cable loss will drop the antenna noise to 7.5 K and our signal to 15 K, and then add 145 K of its own thermal noise, resulting in a noise level of 152.5 K with a signal level of 15 K. The signal-to-noise power ratio converted to dB are10 × log(15/152.5) = –10.07 dB signal-to-noise. Our cable with only 3 dB of loss has buried our signal 10 dB below the noise! From these examples, you can see that although a little loss in front of the LNA might be tolerated in terrestrial communications, it can be disastrous for space communications.

Receiver (Total System) Noise Figure Equation

The noise figure of a receiver requires a combined analysis of noise and gains of the cascaded components between the antenna and the speaker. Usually, one can ignore everything after the first or second IF. However, if gain levels are available, it can be instructive to analyze your entire system. QST

STRAYS

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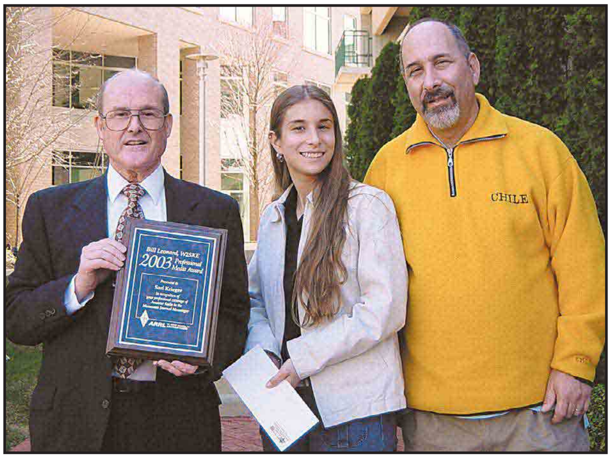

Roanoke Division Director Dennis Bodson, W4PWF, presents Sari Krieger with the 2003 Bill Leonard, W2SKE, Professional Media Award. Krieger, a staff writer with Virginia's *Potomac News* and the *Manassas Journal Messenger*, was honored for her story about the negative effects of Broadband over Powerline (BPL) on ham radio. Sari's father David Krieger, AK2A, attended the presentation as he traveled through the area, heading south from his home on Long Island.