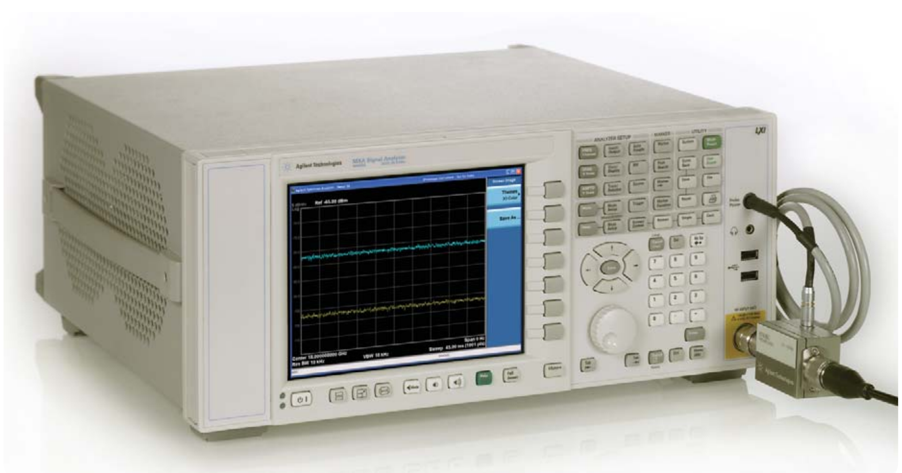
Agilent
Preamplifiers and System Noise Figure

Application Note



Agilent Technologies

Preamplifiers

A preamplifier is an amplifier used in a way such that it usually precedes another amplifier to prepare an electronic signal for further amplification or processing.

It is usually a low noise amplifier with moderate gain. For example, in communications systems, the preamplifier is used to amplify the very small signals received by the antenna and is often located very close to the antenna.

Using a preamplifier with low noise, the noise of all the subsequent stages is reduced by the gain of the preamplifier and the noise of the preamplifier is injected directly into the received signal. A preamplifier is required to boost the desired signal power while adding as little noise and distortion as possible so that the retrieval of this signal is possible in the later stages in the system.

The following sections will give a description of noise and the effect an amplifier has on the sensitivity and noise figure of a system as well as a method for choosing the correct amplifier to meet your measurement needs.

Noise in Microwave Systems

Noise power is a result of random processes, such as the flow of charges or charge carriers in solid state devices or materials, propagating through the ionosphere or other ionized gas. It is also caused by thermal vibrations in any component at temperatures above absolute zero. Noise found in a microwave system can be generated from external sources, or the system itself. The noise level of a system sets the lower limit on the magnitude of a signal that can be detected in the presence of the noise. So, to achieve the best performance you need to have a minimum residual noise level.

Typically, noise can be categorized as follows:

Thermal noise – also known as Johnson or Nyquist noise, is caused by thermal vibrations of bounded charges.

Shot noise - is generated by random fluctuations of charges in devices.

Flicker noise – also known as 1/f noise, occurs when the power varies inversely with frequency. For example in solid state devices and vacuum tubes.

Plasma noise - is caused by the randomized motion of charges in ionized gas.

Noise power is usually characterized by an equivalent noise figure or noise temperature. These terms are explained in more detail in the following section.

Noise figure is used to determine the amount of noise a specific component will add to the system and is usually expressed in decibels (dB). Noise figure (NF) is defined as the ratio of the input signal-to-noise ratio (SNR) to the output SNR. In other words,

$$NF = \frac{(S/N)_{in}}{(S/N)_{out}} \qquad \text{(Equation 1)}$$

Where $(S/N)_{in}$ is the signal-to-noise ratio at the input, *and* $(S/N)_{out}$ is the signal-to-noise ratio at the output of the device under test. Note that S/N at the output will always be smaller than the S/N at the input, due to the fact that circuits always add to the noise in a system.

A simple and short introduction of noise is given here. More comprehensive explanation on noise can be found in *Agilent Fundamentals of RF and Microwave Noise Figure Measurements AN 57-1*.

Noise Figure in a Cascaded System

In a typical microwave system, the input signal travels through a cascade of many different components, each of which may degrade the signal-to-noise ratio to some degree.

The cascaded noise figure is calculated using gain and noise figure in linear terms rather than in decibels (dB). As the following equation shows, cascaded noise figure is affected most profoundly by the noise figure of components closest to the input of the system (as long as some positive gain exists in the cascade). If only loss exists in the cascade, then the cascaded noise figure equals the magnitude of the total loss. The following equation is used to calculate the cascaded noise figure as a ratio based on ratio values for gain and noise figure.

Noise factor contributions of each stage in a chain follow this equation:

$$F_{cascade} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots\cdots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}} \qquad \text{(Equation 2)}$$

Where the power gains and noise factors are the linear, not logarithmic, quantities. Note that the cascaded noise figure is based solely on the individual noise figure and gain at each stage.

Noise Figure Improvement

Amplifiers can be added to noise figure measurement systems to significantly decrease system noise figure. Table 1 shows typical noise figure reduction achieved with Agilent's 83000 family of amplifiers; these were calculated using equation 2. Note that the reduced system noise figure is dominated by the preamplifiers.

Table 1. Noise figure improvement using amplifiers

Amplifier model number	Frequency (GHz)	Max NF (dB)	Min gain (dB)	F_{sys} without preamp (dB) 13	15	20	30
83006A	0.01-0.2	13	20	—	13.1	13.2	14.8
	0.2-18	8		8.1	8.2	8.6	12.1
	18-26.5	13		—	13.1	13.2	14.8
83017A	0.5-18	8	25	8.0	8.1	8.2	9.8
	18-26.5	13		—	13.0	13.1	13.6
83018A	1-2	10	23	10.0	10.1	10.2	11.8
	2-20	10	27	10.0	10.0	10.1	10.8
	20-26.5	13	23	—	13.0	13.1	14
83020A	2-20	10	30	10.0	10.0	10	10.4
	20-26.5	13	27	—	13.0	13.1	13.4
83050A	2-26.5	6	21	6.1	6.2	6.5	9.5
	26.5-50	10		10.0	10.1	10.2	11.8
83051A	0.045-2	12	23	12.0	12.0	12.1	13.2
	2-26.5	6		6.1	6.2	6.3	9.5
	26.5-50	10		10.0	10.1	10.1	11.8
87405B	0.01-4	5	22	5.2	5.3	5.8	9.8
87405C	0.1-4	6	25	6.1	6.1	6.3	8.5
	4-18	4.5	25	4.5	4.6	5.0	7.7

Preamplifiers in Spectrum Analyzer Applications

By placing an appropriate preamplifier in front of a spectrum analyzer, you can obtain a system (preamplifier/spectrum analyzer) noise figure that is lower than that of the spectrum analyzer alone. To the extent that you lower the noise figure, you also improve the system sensitivity. However, a preamplifier also amplifies noise, and this output noise can be higher than the effective input noise of the analyzer. A spectrum analyzer using log power averaging displays a random noise signal 2.5 dB below its actual value. For more information refer to Agilent Application Note 150, *Spectrum Analysis Basis,* August 2006, 5952-0292. Rather than develop a lot of formulas to see how preamplifiers improve sensitivity, this section shows two extreme cases and when each might apply.

First, if the noise power out of the preamplifier (in a bandwidth equal to that of the spectrum analyzer) is at least 15 dB higher than the displayed average noise level (DANL) of the spectrum analyzer, then the noise figure of the system is approximately that of the preamplifier less 2.5 dB. Simply connect the preamplifier to the analyzer and note what happens to the noise on the display. If it goes up by 15 dB or more, then you have fulfilled this requirement.

In theoretical terms, this is written as follows:

If $NF_{pre} + G_{pre} \geq NF_{sa} + 15$ dB,

Then $NF_{sys} = NF_{pre} - 2.5$ dB

On the other hand, if the noise power out of the preamplifier (again, in the same bandwidth as that of the spectrum analyzer) is 10 dB or more lower than the DANL on the analyzer, then the noise figure of the system is that of the spectrum analyzer less the gain of the preamplifier. You can test by inspection. Connect the preamplifier to the analyzer; if the displayed noise does not change, then you have fulfilled the requirement. If you have the equipment at hand, simply connect the preamplifier to the analyzer, noting the DANL, and subtracting the gain of the preamplifier to obtain the sensitivity of the system.

This is expressed as follows:

If $NF_{pre} + G_{pre} \leq NF_{sa} - 10$ dB,

Then $NF_{sys} = NF_{sa} - G_{pre}$

Of course, there are preamplifiers that fall in between these extremes. Figure 1 shows how to determine system noise figure using the noise figures of the spectrum analyzer and preamplifier and the gain of the amplifier. The graph in Figure 1 is used by first determining $NF_{PRE} + G_{PRE} – NF_{SA}$. If the value is less than zero, find the corresponding point on the dashed curve and read system noise figure as the left ordinate in terms of dB with respect to $NF_{SA} – G_{PRE}$. If $NF_{PRE} + G_{PRE} – NF_{SA}$ is a positive value, find the corresponding point on the solid curve and read system noise figure as the right ordinate in terms of dB with respect to NF_{PRE}.

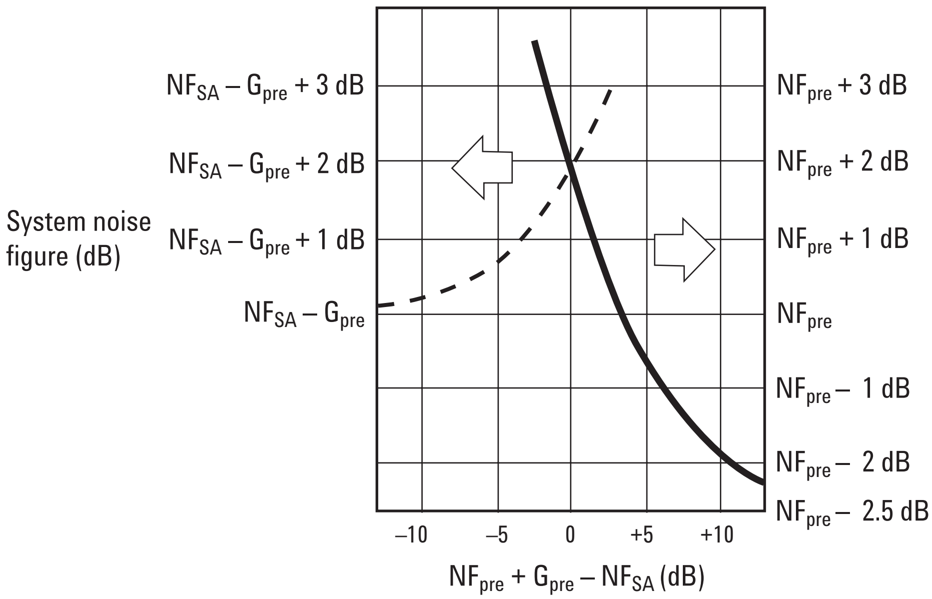


Figure 1. System noise figure for sinusoidal signals

Testing the two previous extreme cases, you can see that as $NF_{PRE} + G_{PRE} – NF_{SA}$ becomes less than –10 dB, the system noise figure asymptotically approaches $NF_{SA} – G_{PRE}$. As the value becomes greater than +15 dB, system noise figure asymptotically approaches NF_{PRE} less 2.5 dB. The next section shows two numerical examples using the same spectrum analyzer noise figure of 24 dB.

How to choose the right preamplifier

In order to choose the correct preamplifier, you must look at your measurement needs and determine what is required: the best sensitivity or widest measurement range.

Case 1: Best sensitivity without concern for measurement range

Choose a high-gain, low-noise-figure preamplifier so that your system takes on the noise figure of the preamplifier, less 2.5 dB.

In the example that follows, these expressions are used to show how a preamplifier affects sensitivity. Assume that the spectrum analyzer has a noise floor of –110 dBm in a 10 kHz resolution bandwidth and a noise figure of 24 dB and the preamplifier has a gain of 36 dB and a noise figure of 8 dB. All you need to do is to compare the gain plus noise figure of the preamplifier to the noise figure of the spectrum analyzer. The gain plus noise figure of the preamplifier is 44 dB, more than 15 dB higher than the noise figure of the spectrum analyzer, so the noise figure of the preamplifier/spectrum-analyzer combination is that of the preamplifier less 2.5 dB or 5.5 dB. In a 10 kHz resolution bandwidth, our preamplifier/analyzer system has a sensitivity of:

$$= NF_{sys} + kT_BB + 10\log(RBW/1) = 5.5 - 174 + 40$$

$$= -128.5 \text{ dBm}$$

Where N_{in} is the input noise power

and

$kT_BB = -174$ dBm/Hz at room temperature

This is an improvement of 18.5 dB over the –110 dBm noise floor without the preamplifier.

There might, however, be a drawback to using this preamplifier, depending upon our ultimate measurement objective. If you want the best sensitivity but no loss of measurement range, then this preamplifier is not the right choice. Figure 2 illustrates this point. A spectrum analyzer with a 24 dB noise figure will have a DANL of –110 dBm in a 10 kHz resolution bandwidth. If the 1 dB compression point for that analyzer is 0 dBm, the measurement range is 110 dB. When you connect the preamplifier, you must reduce the maximum input to the system by the gain of the preamplifier to –36 dBm. However, when you connect the preamplifier, the DANL will rise by about 17.5 dB because the noise power out of the preamplifier is that much higher than the analyzer's own noise floor, even after accounting for the 2.5 dB factor. It is from this higher noise level that you subtract the preamplifier gain. With the preamplifier in place, the measurement range is 92.5 dB, 17.5 dB less than without the preamplifier. The loss in measurement range equals the change in the displayed noise when the preamplifier is connected.

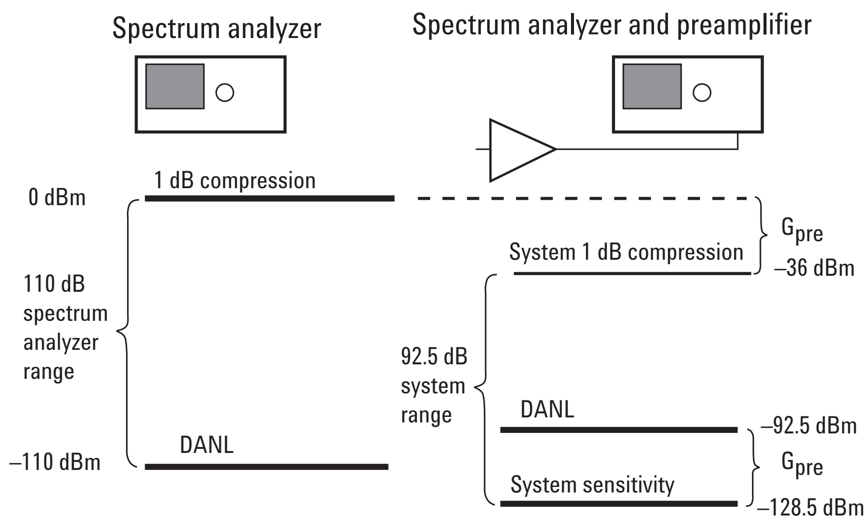


Figure 2. Example of a preamplifier changing system sensitivity

Case 2: Better sensitivity without reducing the measurement range

Choose a lower-gain preamplifier that meets the second case criteria explained in the section *Preamplifiers in Spectrum Analyzer Applications,* that is the sum of the preamplifiers gain and noise figure must be at least 10 dB less than the noise figure of the spectrum analyzer. In this case the displayed noise floor will not change noticeably when you connect the preamplifier, so although you shift the whole measurement range down by the gain of the preamplifier, you end up with the same overall range that you started with. Alternatively, you can use the input attenuator of the spectrum analyzer to effectively degrade the noise figure (or reduce the gain of the preamplifier, if you prefer). For example, if you want slightly better sensitivity but cannot afford to give up any measurement range, you can use a preamplifier with 30 dB of RF input attenuation on the spectrum analyzer. This attenuation increases the noise figure of the analyzer from 24 to 54 dB. Now the gain plus noise figure of the preamplifier (36 + 8) is 10 dB less than the noise figure of the analyzer; this now meets the second case criteria described in the *Preamplifiers in Spectrum Analyzer Applications* section.
The noise figure of the system is now:

$$\begin{aligned} NF_{sys} &= NF_{SA} - G_{PRE} \\ &= 54\text{ dB} - 36\text{ dB} \\ &= 18\text{ dB} \end{aligned}$$

This represents a 6 dB improvement over the noise figure of the analyzer alone with 0 dB of input attenuation. So sensitivity was improved by 6 dB and with virtually no loss in measurement range.

Numerical Examples Using Agilent 87405C Preamplifier

This section examines the impact an amplifier has on the overall system noise figure. The 87405C low noise amplifier, designed for use with Agilent spectrum analyzers or as a standalone amplifier, is used in the following examples. The 87405C preamplifier extends of the existing 87405B (10 MHz to 4 GHz) low noise amplifier to 18 GHz.

In this example, the system noise figure is calculated using the Agilent 87405C preamplifier, which has a noise figure of about 5 dB and approximately 25 dB gain. The preamplifier use Type-N connectors and is powered from instrument's probe bias port.

First,

$$NF_{PRE} + G_{PRE} – NF_{SA}$$

$$= 5 + 25 – 24$$

$$= +6 \text{ dB}$$

From the graph of Figure 1, find a system noise figure of about

$$NF_{sys} = NF_{PRE} – 1.1 \text{ dB},$$

$$= 5 – 1.1 = 3.9 \text{ dB}$$

On the other hand, if the gain of the preamplifier is just 10 dB, then

$$NF_{PRE} + G_{PRE} – NF_{SA} = –6 \text{ dB}$$

This time the graph indicates a system noise figure of

$$NF_{sys} = NF_{SA} – G_{PRE} + 0.6 \text{ dB}$$

$$= 24 – 10 + 0.6 = 14.6 \text{ dB}$$

Many modern spectrum analyzers have optional built-in preamplifiers available. With an external preamplifier, you must correct the spectrum analyzer reading with a reference level offset equal to the preamplier gain. Most modern spectrum analyzers allow you to enter the gain value of the external preamplifier from the front panel. The analyzer then applies this gain offset to the displayed reference level value, so that you can directly view corrected measurements on the display.

Preamplifier for Noise Measurements

Since noise signals are typically low-level signals, you often need a preamplifier to have sufficient sensitivity to measure them. However, you need to recalculate sensitivity of the analyzer first. Sensitivity was defined earlier as the level of a sinusoidal signal that is equal to the displayed average noise floor. Since the analyzer is calibrated to show the proper amplitude of a sinusoid, no correction for the signal was needed. But noise is displayed 2.5 dB too low, so an input noise signal must be 2.5 dB above the analyzer's displayed noise floor to be at the same level by the time it reaches the display. The input and internal noise signals add to raise the displayed noise by 3 dB, a factor of two in power. So you can define the noise figure of our analyzer for a noise signal as:

$$NF_{SA}(N) = (\text{noise floor})\text{dBm/RBW} - 10\log(\text{RBW}/1) - kT_BB_{=1} + 2.5\text{ dB}$$

$$= -110\text{ dBm} - 10\log(10{,}000/1) - (-174\text{ dBm}) + 2.5\text{ dB}$$

$$= 26.5\text{ dB}$$

If the same noise floor that is used previously, –110 dBm in a 10 kHz resolution bandwidth, a noise figure of 26.5 dB is obtained.

As was the case for a sinusoidal signal, $NF_{SA}(N)$ is independent of resolution bandwidth and tells you how far above kTB a noise signal must be to be equal to the noise floor of our analyzer. When you add a preamplifier to a spectrum analyzer, the system noise figure and sensitivity improve. However, 2.5 dB factor is accounted for in the definition of $NF_{SA}(N)$, so the graph of system noise figure becomes that of Figure 3. So, you determine system noise figure for noise the same way that you determine a sinusoidal signal.

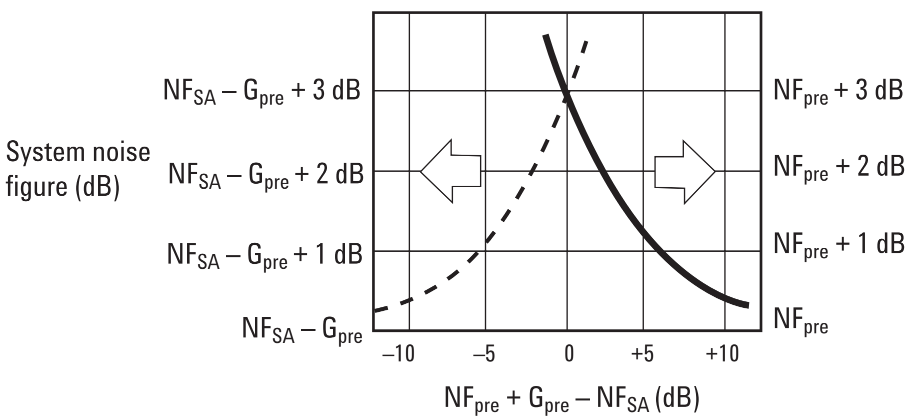


Figure 3. System noise figure for noise signals

Conclusion

Noise is unavoidable in any measurement system. In the case of spectrum analyzers, which are primarily designed for high dynamic range rather than low noise, a preamplifier is usually required to produce good quality measurements in many applications. In summary, a low-noise preamplifier may be beneficial if the device under test (DUT) has low or negative gain or the instrument has a high noise figure. Do not use a preamplifier if a DUT already has significant positive gain, as adding further gain will increase the input noise levels and may also drive the instrument into the non-linear region or exceed the maximum input power to the instrument and thus damaging it.

References

Agilent Application Note 150, Spectrum Analysis Basis, August 2006, 5952-0292.

Agilent Fundamentals of RF and Microwave Noise Figure Measurements, Application Note 57-1, October 2006, literature number 5952-8255E

Noise Figure Measurement Accuracy – The Y-Factor Method, Application Note 57-2, February 2001, literature number 5952-3706E

10 Hints for Making Successful Noise Figure Measurements, Application Note 57-3, literature number 5980-0288EN

Agilent 83000A Series Microwave System Amplifiers Product Overview, November 2002, literature number 5963-5110E

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Other Asia Pacific Countries:
(tel) (65) 6375 8100
(fax) (65) 6755 0042
Email: tm_ap@agilent.com
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