Noise — Friend and Foe of Engineers

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Foe — agreed, but friend? How can noise be appreciated by engineers who labor at the edge of technology when trying to move signals and information as fast as possible from A to B? Isn't noise something we all want to avoid and eliminate? This column addresses engineers who are interested in exploring the concept of utilizing noise for test and measurement purposes. It discusses how white Gaussian noise can be employed as a versatile signal source. A short introduction discusses causes, sources, and quantities relevant to noise, followed by two application examples that utilize noise: noise as a broadband reference and noise load to determine optimal system operation levels.

What Is Noise?

Noise is omnipresent in the universe. With the exception of absolute zero temperature point at 0 Kelvin (0 K), all materials produce noise with a power level proportional to the physical temperature of the material. Noise is generated by random vibrations of conducting electrons and holes in the material. It is often referred to as thermal noise. A variety of other effects generate noise as well, but it would exceed the scope of this document to discuss them all. Noise energy emitted by one single element is rather minuscule, but the almost infinite count of vibrating elements sum up to a significant power level — large enough to challenge us when developing sensitive receivers, or operating with ADCs and DACs that have a high bit resolution, just to name two applications.

White Noise

Thermal noise is "white" and has a Gaussian amplitude distribution. The term "white" specifies constant output power over a linear frequency spectrum, as opposed to "pink" noise that provides constant power over a logarithmic frequency spectrum. Because of this evenly distributed power, certain frequency segments of equal bandwidth provide the same power level with white noise, which can be very helpful when analyzing filters, amplifiers, and system responses. Overall output power of white noise sources is dependent on the specified bandwidth. Output characteristics can be described in different ways:

Power:	dBm, dBm/Hz, dBm/frequency band
Voltage:	V/Hz
Ratios:	ENR (excess noise ratio), noise temperature (K)

The fact that power spectral density is constant over frequency implies that noise power is proportional to bandwidth. If the measurement bandwidth is doubled, the detected noise power is doubled as well and increases by 3 dB. Total power (P) in dBm and spectral power (PS) in dBm/Hz of white noise sources are related by the following equation:

$$P = PS + 10\log(BW).$$

BW is the measured bandwidth, and PS is a characteristic quantity of a particular noise source, usually provided on datasheets. Specific noise sources are built for optimal flatness over the frequency band.

Gaussian Distribution And Crest Factor

Statistical evaluations of related occurring events present always certain kinds of distribution curves. Gaussian distribution, also known as normal distribution, is the most common way events take place. Most white noise sources provide Gaussian distribution of their spectral power.

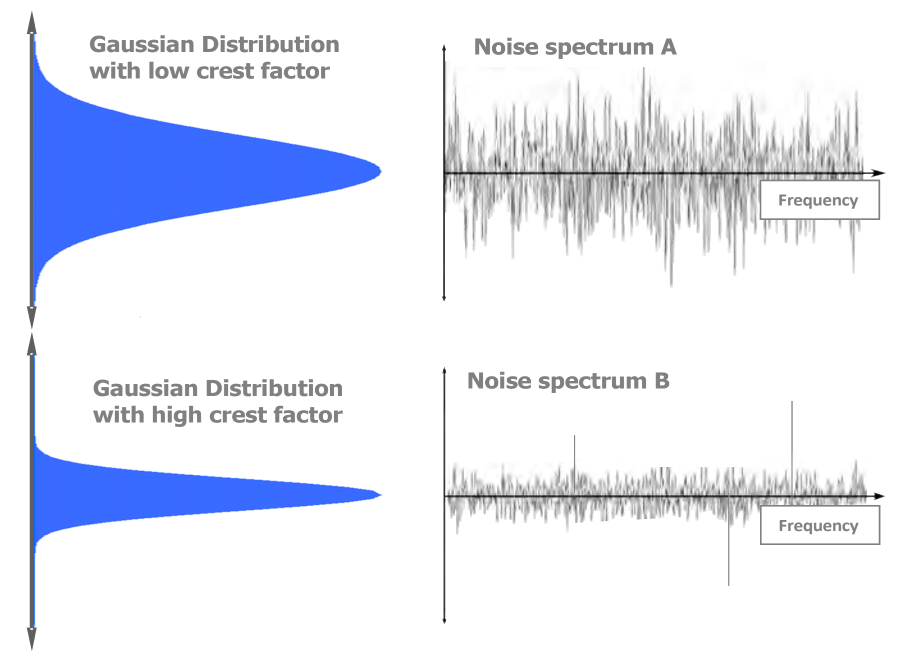

Figure 1 *shows two white noise sources. Spectrum A has a large variance in power distribution, and thus provides a low crest factor. Spectrum B has a high crest factor, so unwanted signal levels are less frequent.*

Why is Gaussian distribution of such importance? The randomness of noise sources requires a mathematical model that allows calculating the probability density of events. Gaussian distribution right and left of the mean probability is of equal size. Crest factor, the peak-to-average ratio, is also an important quantity for noise sources. It allows calculating the likelihood of unwanted events relative to the mean probability. Such renegade events may cause an overload of an amplifier input, distortion of a signal, or a bit error. Obviously, the fewer of those natural but unwanted events happen, the better. High quality white Gaussian noise sources offer crest factors of up to 18 dB, placing the probability of unwanted events far beyond reasonable measurement capabilities.

Application 1: Noise as a Broadband Reference

We discussed two key characteristics of white noise: It offers all frequencies in a specified frequency band simultaneously, and that with a constant power level. These features make noise sources desirable elements whenever analyzing frequency bands of filters, circuits, instruments, or systems, as, for example, filter analysis or spectrum analyzer calibration.

A simple way to calibrate spectrum analyzers is to use a broadband white noise source to monitor the analyzer's frequency response. Noise sources are available with spectral flatness that far exceeds typical spectrum analyzer accuracy; hence, this flat frequency distribution makes white noise sources ideal for calibration purposes. A spectrum analyzer's flatness is influenced by the effects of its internal RF attenuator, preselector, and mixing mode gain variations. Injecting noise into a spectrum analyzer as a reference source can therefore provide an accurate measurement of the amplitude variations versus frequency.

Another way to normalize the errors associated with spectrum analyzer measurement is to employ a signal generator that sweeps the required frequency while the analyzer stores the response. A noise source has several advantages over this approach:

Cost: The cost of a noise source is insignificant compared to the cost of a broadband signal generator with similar output-versus-frequency characteristics.

Size: A noise source can be made much smaller than a signal generator.

Speed: When performing broadband measurements, the oscillator must be set, responses stored, next frequency set, next responses stored, and so on. Even with fast signal generators, this can take quite a long time, depending on the number of samples taken. White noise sources generate all the frequencies simultaneously, so the limiting factor is only the measurement speed of the spectrum analyzer. The procedure requires less time, which dramatically reduces cost.

Accuracy: Noise sources can be accurately measured to within tenths of a dB by NIST-traceable methods.

Application 2: Noise Load to Determine System Behavior — Noise-Power-Ratio (NPR) Measurements

Serious dynamic range problems can occur in systems loaded with multi-channel signals. Any nonlinearity in the system (e.g. an amplifier) causes intermodulation products among the input frequencies. This produces new frequencies that may fall within the bandwidth of other channels, therefore creating distortions. The amount of distortion increases with the number of channels and the degree of amplifier saturation. For example, two uncorrelated tones may, at times, add in-phase to create peak voltages that are about 6 dB higher than the RMS voltage.

The peak-to-RMS voltage ratio increases by 10 log(2n) dB, where n is equal to the number of uncorrelated signals of the same amplitude. Many uncorrelated load signals can be simulated by white Gaussian noise for noise power ratio (NPR) testing. The NPR method is an accurate means of reproducing multi-carrier intermodulation effects and determining the amplifier's performance under worst-case loading conditions.

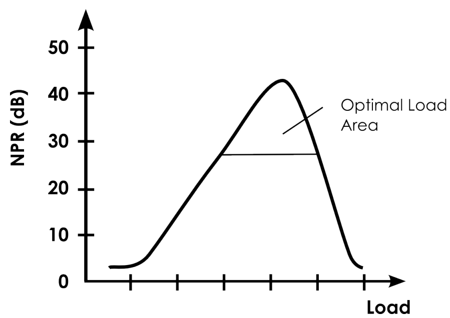

Figure 2: *Plot of NPR vs. loading condition to determine the optimum operating point for maximum SNR.*

Intermodulation testing of amplifiers with only two tones has many shortcomings if the life system is actually loaded with numerous signals. First, the distortion product amplitude may be dependent on the frequency spacing of the input signals. Second, the amplifier will perform differently when loaded with many signals. The peak-to-average ratio of multiple modulated signals is much greater than two or several tones. These large peaks stress the amplifier or device under test (DUT) to a greater degree. The NPR method emulates many signals by loading the amplifier with white Gaussian noise.

Intermodulation distortion manifests itself in two primary ways. In a receiver LNA, adjacent channel signals cause in-band distortion products. For a transmitter power amplifier, distortion of the primary signal will cause interference in adjacent channels. Both cases are closely related and can be accounted for with the noise power ratio (NPR) test. NPR is a measure of distortion produced in a particular band by a device that is loaded with just white noise. Measurement of NPR versus output power, or loading, is used to define the optimum operating point for maximum signal-to-noise ratio (SNR). The NPR of a DUT is degraded primarily by two factors. The first is the distortion products that are produced under high loading conditions. The second is the noise floor of the amplifier that will become dominant under very low loading conditions. By making numerous measurements with different loading levels, a curve will be generated, as shown in *Figure 2*. NPR is poor at low loading levels because the amplifier is being operated near its own noise floor. The NPR is also poor at very high loading levels. But the slope on this side of the curve is steeper since the dis-

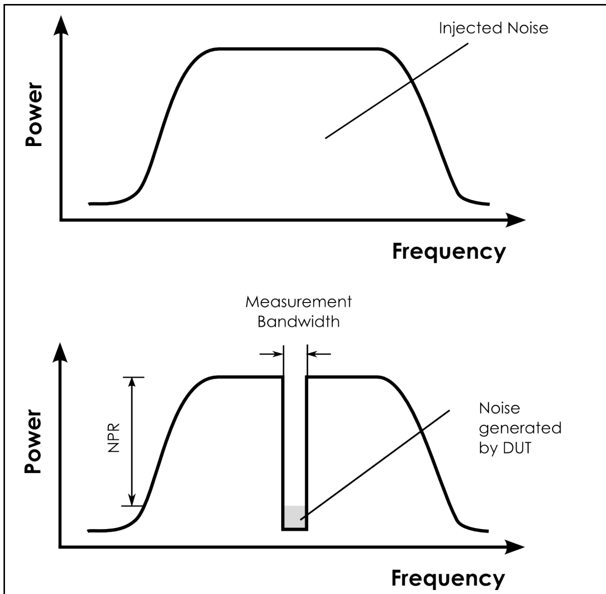

Figure 3: *Output noise spectrum during NPR Measurement. Noise is injected over the whole operating bandwidth (a). Now, a notch filter is applied to suppress a known amount of power in a specific bandwidth (b). The excess of measured power is generated by the DUT.*

tortion products are dominant in this case. If distortions are caused by nth-order harmonics, intermodulation products increase by (n-1) dB for every 1 dB increase of the loading level. For example, for third-order distortions, intermodulation products increase 2 dB for every 1 dB increase of the loading level. Systems are often operated at signals a few dB below the point of maximum NPR. To perform an NPR test, an accurate level of white Gaussian noise is applied to the amplifier. A bandstop (notch) filter is then inserted to create a "quiet" channel. The NPR is the ratio between the noise power measured with and without the notch filter (*Figure 3*).

Conclusion

Noise can indeed help to solve test and measurement challenges for engineers. The applications discussed above — noise as a broadband reference and noise to measure system load behavior — are just two of many. A wide variety of noise sources available for specific applications. They are affordable, and offer a flat response over a wide frequency band.