Noise is a central topic in analog design, but unfortunately there is a large amount of confusion and misinformation regarding noise. In broad terms, the noise of a circuit affects its precision, its accuracy, and sets the limit for the smallest signal that can be measured. It is important not only to reinforce the basics of noise in order to successfully design sensitive analog circuits, but also to relate them to the specifications of the end system in order to make them more meaningful.

A popular definition of noise is: any unwanted signal that interferes with the measured value of the signal of interest. This is a very broad definition, encompassing DC or AC noise sources, intrinsic or extrinsic, random or repeatable, reducible or irreducible. To constrain this definition further, random noise can be defined as anything that interferes with the repeatability of the measurement. Random noise is what puts a limit on the smallest signal that can be measured in the system.

Noise is generated in all components of a circuit, including the sensor, amplifiers, converters, digital processing, transmitters or radios, and power supplies. Noise can also be coupled in from the outside world.

Extrinsic Noise vs Intrinsic Noise

It is important to make the distinction between extrinsic noise, which comes in to the circuit from the outside, and intrinsic noise, which is generated within the circuit. There is a gray area here, for example, if a power supply ripple is coupled into the circuit through the finite power-supply rejection ratio of an amplifier, the noise source is external to the signal path, but internal to the whole circuit. For the purpose of this discussion, this can be considered extrinsic noise because the power supply ripple comes into the signal path from the outside and it can be reduced.

Extrinsic noise requires three elements: a source of the noise, a coupling path into the circuit, and a receiver, which is generally a sensitive node in the signal path. Extrinsic noise is often at discrete frequencies and may be intermittent. Extrinsic noise is difficult to calculate in most cases, but generally it is reducible, meaning it can be mitigated by good circuit design practice, such as proper grounding techniques, shielding, layout, and decoupling.

Intrinsic noise, on the other hand, is generated within the signal path of the circuit. In many cases, the intrinsic noise is caused by fundamental physical properties, such as the random thermal movement of particles. In these cases, the intrinsic noise is not reducible for a given frequency, and is spread out across a wide range of frequencies. This irreducible source of noise sets the limit for the smallest signal that can be measured, assuming the right design choices were made to reduce the extrinsic noise.

The Units of Noise

Figure 1 describes several units that are used to specify noise; specifically, peak-to-peak noise, root-mean-square (RMS) noise, and noise spectral density (NSD). Peak-to-peak noise depends on just two points in an entire waveform, and those two points are outliers. The peak-to-peak noise is not a very repeatable measurement, and it is dependent on the bandwidth of the circuit. It is useful in certain situations, such as comparing against a converter input range in an oversampled system with high gain. RMS noise is dependent on all of the points in the waveform, and is related to the noise power, which is much more predictable and much easier to quantify. Like the peak-to-peak noise, the RMS noise is also dependent on the bandwidth of the circuit.

The NSD removes the bandwidth as a factor by normalizing the RMS noise for a 1Hz-wide frequency band for all points along the frequency spectrum. NSD is difficult to measure, but it is the most general because it can be used to determine the RMS noise of the circuit for any frequency range. More specifically, the RMS noise of a circuit with a spectrally flat NSD is equal to the NSD.
times the square root of the noise equivalent bandwidth (NEB). The NEB is the theoretical brick-wall filter that would let in the same total noise as the real filter. For a single pole filter, the NEB is 1.57 times the -3dB bandwidth, and the NEB can be looked up for various types of higher-order filters.

**Combining Noise Sources**

When combining the various noise sources in the circuit into a total noise value, there are some common problems that must be avoided. First is matching the units. It’s usually preferable to use RMS noise rather than NSD because RMS noise has already taken bandwidth into account and some noise sources may have different bandwidths than others. Whatever units are chosen, it is important to be consistent throughout the calculation in order to avoid errors. Second, refer noise sources to the same point in the circuit. Noise is usually referred to the input of the circuit (RTI) because that allows the noise to be compared directly against the signal, but in some cases it is referred to the output (RTO). Whether the calculation is RTI or RTO, use the gain or propagation of gains through the circuit to refer all noise sources to the same point before combining them. For example, if a noise source at the output of a gain stage is calculated (RTO), but the noise will be combined with other sources at the input of the gain stage (RTI), then the RTO noise source should be divided by the gain to get the equivalent RTI noise. Third, the noise power adds directly, which means the noise voltage adds as the root sum of squares (RSS).

**Common Types of Intrinsic Noise**

There are many types of intrinsic noise, but most engineers will only use a few of these types in day-to-day analysis. Voltage noise is associated mainly with op amps and other types of amplifiers. It is a noise voltage modeled in series with the amplifier input. Voltage noise does not scale with the source resistance, which is defined as the total resistance that is presented to the input of that amplifier by the sensor or external resistors. Current noise, on the other hand, is a noise current generated at the input of a device. The current noise generates a voltage as it flows through the source resistance, in accordance with ohms law. The NSD curve starts to climb upward at very low frequencies. The noise in this region where the NSD is increasing for lower frequencies is the 1/f noise; so named because the slope of the noise power is approximately 1/f. White noise, or broadband noise, is the term for the region with flat NSD at the higher frequencies of the NSD curve. Johnson noise, also called thermal noise or resistor noise, is a source of noise in all resistors associated with the random thermal motion of electrons in the resistive material. Other types of noise, encountered less frequently, include quantization noise, shot noise, popcorn noise, and avalanche noise.

**Component Noise: Resistors, Amplifiers, and ADCs**

The equation for the RMS noise of a resistor R over a bandwidth B is $\sqrt{4kTRB}$, as shown in Figure 3, where $k$ is Boltzmann’s constant and $T$ is the temperature in Kelvin. The bandwidth, $B$, is often taken to be 1Hz, which changes the result to NSD rather than RMS noise. Two useful shortcuts to this equation are that at 25°C, $1\Omega$ is about 0.128 nV/$\sqrt{Hz}$ and that $1k\Omega$ is about 4nV/$\sqrt{Hz}$. Then the noise scales with the square root of the resistance, for example, 100$\Omega$ has an NSD of 1.28nV/$\sqrt{Hz}$. Although temperature is a factor in this equation, it is rarely an important factor, since a
temperature increase from 25°C to 85°C only produces a 10% increase in noise.

Amplifiers and converters specify noise differently. Amplifier data sheets typically provide a voltage noise and a current noise. The voltage noise specification will be the NSD in the flat band region, 1kHz or higher, and often a peak-to-peak noise from 0.1Hz to 10Hz to indicate the 1/f noise level. Current noise is typically specified as a flat band NSD and only occasionally as a peak-to-peak value from 0.1Hz to 10Hz.

ADC datasheets usually specify signal-to-noise ratio (SNR) with a nearly full-scale signal applied, or in some cases RMS noise is specified directly. Converting the ADC noise component to RMS is very useful to compare to the other noise sources in the signal chain. Signal-to-noise ratio is the RMS input range divided by RMS noise. Rearranging the equation, the RMS noise can be obtained by dividing the RMS input range (the analog input range divided by $\sqrt{2}$) by the SNR converted to V/V.

The source resistance in front of an amplifier is what translates voltage noise and current noise, and allows them to be combined. Therefore the value of the source resistance is needed in order to determine the total noise of an amplifier circuit. The noise component caused by the current noise increases proportional to the source resistance, so the current noise will dominate for high source resistance. If the current noise dominates, a lower-current-noise amplifier, such as a FET input, can usually be found. For very low source resistance, voltage noise becomes the dominant factor for the noise. If the voltage noise dominates, a low voltage noise amplifier should be chosen, but the designer should be aware that the tradeoff to get lower voltage noise is generally higher power consumption. There may be a point for medium source resistances where the thermal noise of the source resistance itself is the dominant noise component, in which case the best way to reduce the noise is to reduce the source resistance if that is possible.

**DESIGNING A SYSTEM FOR NOISE PERFORMANCE**

From a system level, a few terms must be defined in order to determine what it means to optimize the noise of a system. These are resolution, dynamic range, and sensitivity. Different systems will optimize one or the other of these parameters, for example one might sacrifice dynamic range to get higher sensitivity. This section quotes the definitions obtained from test and measurement companies, please see the webcast for the sources that are referenced.

There is more than one answer to the question of how low the noise needs to be in an analog design. In many, but not all cases, the system is designed for the best possible noise performance in the target category, but there are always constraints to observe in a real world system. These constraints include power, performance, cost, and complexity. Many of these constraints will tradeoff directly or indirectly against the noise, so it is critical to understand the tradeoffs from a cost and benefit perspective in order to successfully design a low noise system. Even in other cases, where there is a definite noise level below which the system noise is good enough and there is no benefit to designing for the lowest possible noise, the correct tradeoffs must be made.

**Definitions in System Noise**

Resolution is defined as the total number of discrete levels that can be detected by the instrument. The resolution is specified in units of bits, counts, or digits, depending on the output of the instrument. This is fixed by the ADC in the device, so it does not depend on the noise. Effective resolution, on the other hand, depends on the noise, and can be defined as the smallest portion of the input signal change that the instrument can detect reliably.

Sensitivity refers to the smallest change in the measurement that can be detected. The sensitivity of the instrument is specified in units of the measured value such as volts, ohms, amps, or degrees. To quote Keysight: “Whereas resolution is a measure of the smallest change in the output (or indication) that is possible, sensitivity refers to the smallest change in the input (or stimulus) that causes a discernible change in the output.”

Dynamic range is the ratio of the maximum level of a
parameter to the minimum detectable value of that parameter. Dynamic range relates the full-scale signal range to the sensitivity of the device, and is generally specified in dB. It is often synonymous with the effective resolution.

**System Noise Considerations**

Figure 4 shows an example signal chain where different noise sources have different noise equivalent bandwidth (NEB). In such cases, the NSD of each source cannot be added together. The RMS noise must be used instead because the bandwidths for each noise source are taken into account separately. The smallest NEB after the noise source is used for noise calculation. To see why that is, consider the gain amp at the left, which is generating noise across its full 50kHz bandwidth, but the noise between 1kHz and 50kHz is filtered out in the Sallen-Key filter that follows, so the total noise is only affected by the noise generated by the gain amplifier from dc to 1kHz. Looking only at the NSD of these components, it appears that the gain amplifier, which is 300 nV/√Hz RTO, should dominate the total noise. This is misleading because the gain amplifier has the smallest bandwidth, and in fact, all of the noise sources have similar RMS noise values once the NEB of each stage is taken into account.

A common question to consider for noise performance is how much gain to take and where to take it. The usual answer is to take as much gain as possible as early as possible in the signal chain. But what is the effect of taking gain? Gain reduces the contribution of the noise sources after the gain stage, but at the same time it makes the input range smaller. To elaborate, the input signal range is the ADC input range divided by the gain, which is the reason increasing the gain reduces the input signal range. Noise sources after the gain stage are divided by the gain when they are referred to input to compare to the signal. In other words, higher gain increases the signal amplitude at the output of the gain stage, but it does not affect the noise sources after the gain stage, so the signal is stronger relative to the noise. Because of these two effects of taking gain, it is apparent that at low values of gain where the output noise sources are dominant, the dynamic range is constant, but the sensitivity improves with increasing gain. At higher gains where the input noise sources are dominant, the sensitivity is constant, so the dynamic range goes down inversely proportional to the gain. Though this may sound like it sets a maximum useful level for the gain, keep in mind the components after the gain stage aren’t necessarily fixed. When dynamic range is not critical, high gain can be taken and cheaper, lower power, and noisier devices can be used after the gain stage without affecting the noise performance.

Be clear about the benefits of a trade-off. The most commonly over-designed component in a signal chain is the ADC driver. The datasheet might suggest to use an ADC driver amplifier with 1/10th the noise of the ADC. This makes sense when measuring the performance of the ADC, but most circuits are not designed to benchmark the ADC performance. While it’s true that there is 3dB more noise in a system where the ADC driver and the ADC have the same noise, the first-order relationship is that amplifier noise goes down with the square root of power, meaning it might take 100 times more power to choose an amplifier with 1/10th the noise of the ADC, and the benefit is only 3dB improvement in noise. Instead of making design choices this way, keep the system goals in mind. For example, in a sensor interface design, start with the sensor and make the tradeoffs that give the best representation of the sensor signal within the design criteria.

**A Low Noise Design Flow**

For a simple signal chain in the case where the input signal is known, a low noise design flow can be defined as follows: first, know the signal characteristics, including the maximum signal range, frequency range,
noise, and source impedance. Then, set the desired filter frequencies, setting the pass band as small as possible without affecting the signal in order to minimize out-of-band noise. Third, calculate the sensor noise and choose the input amplifier based on noise and any other design criteria, such as errors, power, function, and configuration of the device. Fourth, choose the gain and determine the noise requirements and other requirements for the output circuitry. Finally, choose real output components, re-adjusting the gain as necessary to match requirements. In this way, it is possible to arrive quickly at a design with excellent noise performance without overdesigning, as shown in the step-by-step example in this webcast.

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