Industry Article

Resolving the Signal Part 4: Understanding Effective Noise Bandwidth in Precision Delta-Sigma ADCs

April 11, 2018 by Bryan Lizon, Texas Instruments

Part 4 of this “Resolving the Signal” article series covers noise in delta-sigma ADCs focuses on understanding basic effective noise bandwidth (ENBW) topics.

This 12-part article series focuses on the impact of noise in delta-sigma ADCs. Part 4 covers noise in delta-sigma ADCs and focuses on understanding basic effective noise bandwidth (ENBW) topics.

Understanding analog-to-digital converter (ADC) noise can be challenging even for the most experienced analog designers. Delta-sigma ADCs have a combination of quantization and thermal noise that varies depending on the ADC’s resolution, reference voltage, and output data rate. At a system level, noise analysis is further complicated by additional signal-chain components, many of which have dissimilar noise characteristics that make them challenging to compare.

If you want to be able to estimate the noise in your system, however, you must understand how much noise each component contributes, how one component’s noise may affect another and which noise sources dominate. Although this may seem like a difficult task, you can use a signal chain’s effective noise bandwidth (ENBW) to help simplify the process.

To that end, part 4 of this “Resolving the Signal” article series about noise in delta-sigma ADCs focuses on understanding basic ENBW topics such as:

- What is ENBW?
- Why do you need ENBW?
- What contributes to the system’s ENBW?

Part 5 will continue the ENBW discussion by stepping through a simple design example using a two-stage filter to explore these subjects:

- How to calculate ENBW.
- How system changes affect ENBW.

Other Articles in this Series

Resolving the Signal: Introduction to Noise in Delta-Sigma ADCs

Resolving the Signal: Introduction to Noise in Delta-Sigma ADCs Part 2

Resolving the Signal: Introduction to Noise in Delta-Sigma ADCs Part 3

What is ENBW?

Since ENBW is an abstract concept, let’s use the simple analogy of doors and windows on a cold night to understand it more easily. To reduce your energy costs and save money, you need to keep all of your doors and windows closed as much as possible in order to limit the amount of cold air entering your home. In this case, your home is the system, your doors and windows are the filter, the cold air is noise and the ENBW is a measurement of how open (or closed) your doors and windows are. The larger the gap (ENBW), the more cold air (noise) gets into your home (system), and vice versa, as shown in Figure 1.

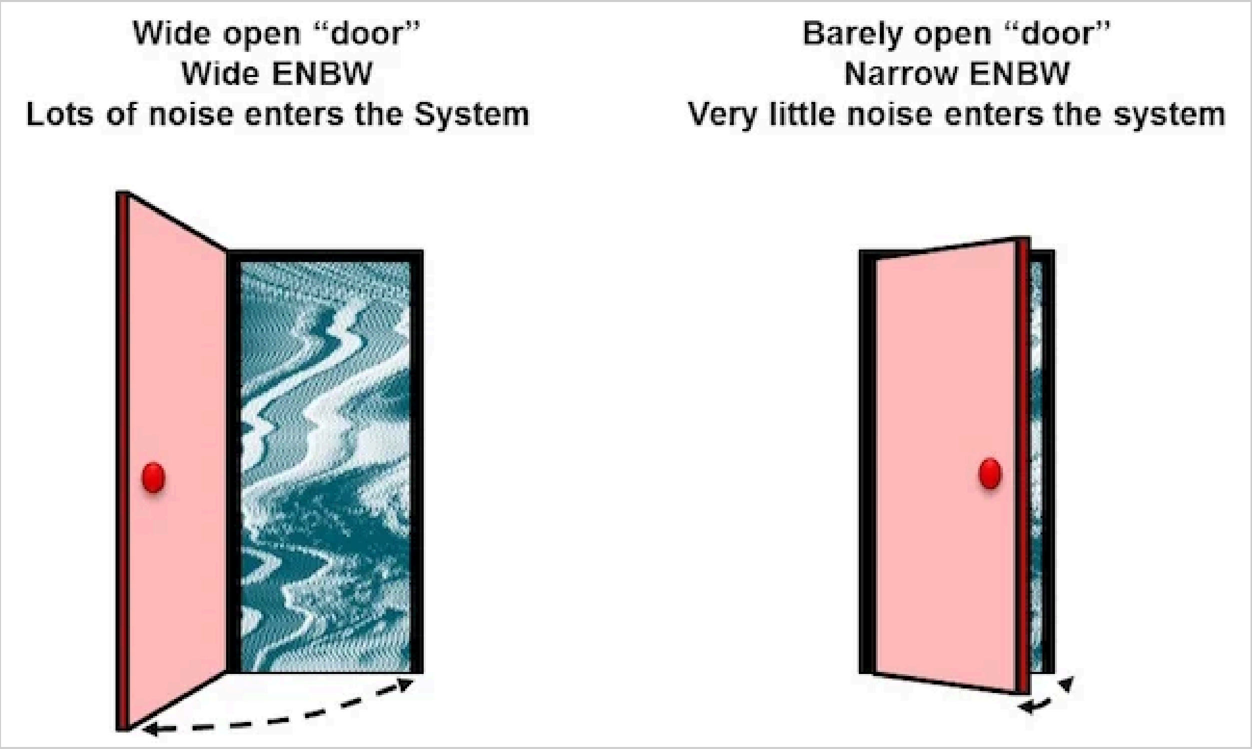
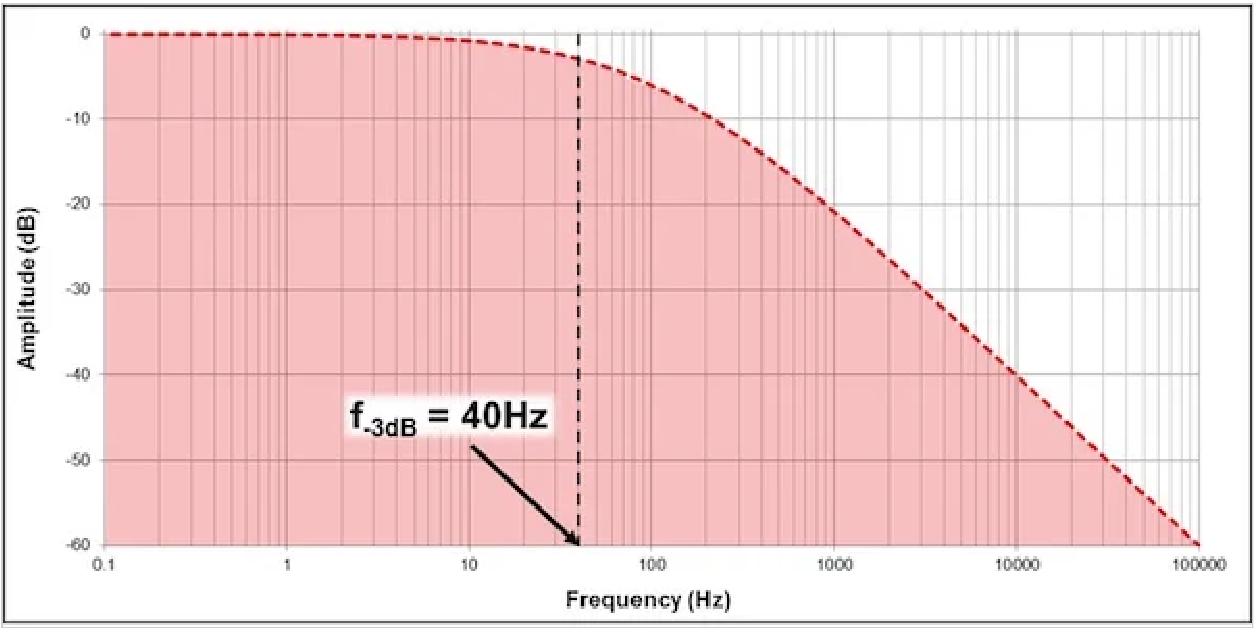


Figure 1. Wide-open door = more noise (left); barely open door = less noise (right)

In general signal-processing terms, a filter's ENBW is the cutoff frequency, f_C, of an ideal brick-wall filter whose noise power is approximately equivalent to the noise power of the original filter, H(f). Relating this definition back to the door and window analogy, a system's ENBW is equivalent to combining the opening widths of each door and window – which may all be different – into one definable value that applies equally to them all. This simplification makes it much easier to understand how much "cold air" is getting in.

As an example, let's simplify a single-pole, low-pass resistor-capacitor (RC) filter (Figure 2, top) into an ideal brick-wall filter (Figure 2, bottom). To do so, calculate the noise power under the actual filter response using integration. This calculated value is the original filter's ENBW, which then becomes the cutoff frequency, f_C, of an analogous ideal brick-wall filter.



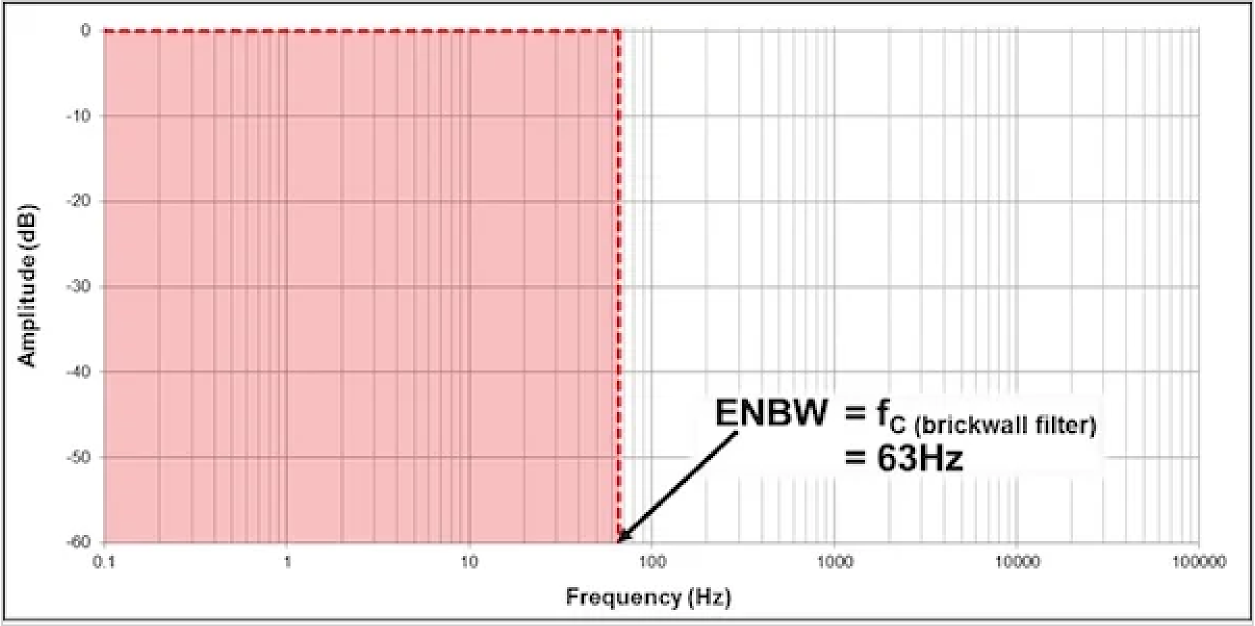


Figure 2. Single-pole RC filter response (top); ENBW plot for the RC filter (bottom)

In this case, you can calculate a single-pole, low-pass filter's ENBW using the direct-integration method, or you can use Equation 1, which relates the original RC filter's 3dB point to its ENBW:

$$ENBW_{1-pole\ RC\ Filter} = 1.57 * f_{-3dB}$$

TI's Precision Labs training series on amplifier noise provides more information about how this formula was derived.

With this simple example, ENBW is defined as the transformation from a real-world filter response to an ideal filter response. But let's discuss the motivation for using this technique and see how it can help simplify your noise analysis calculations.

Why do you Need ENBW?

To understand why you need ENBW, let's assume that you want to use an ADC with no filtering to measure low-level resistive-bridge signals whose typical full-scale output can be as low as 10mV. To accomplish this, you'll need to add an amplifier at the ADC's input to gain up your signals of interest above the ADC's noise floor, as well as widen the ADC's dynamic range. With no other filtering, the amplifier passes virtually all of its noise to the ADC. In this case, the noise is limited only by the amplifier's bandwidth, which could be thousands of kilohertz or more.

Fortunately, you'll also need to add an anti-aliasing filter after the amplifier. This filter performs two functions: first, it limits unwanted signals from folding back into the passband; and second, it reduces the signal chain's ENBW far more than the amplifier's bandwidth alone, given that Equation 2 is generally true:

$$BW_{Filter} \ll BW_{AMP}$$

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Figure 3 models the new ADC input stage.

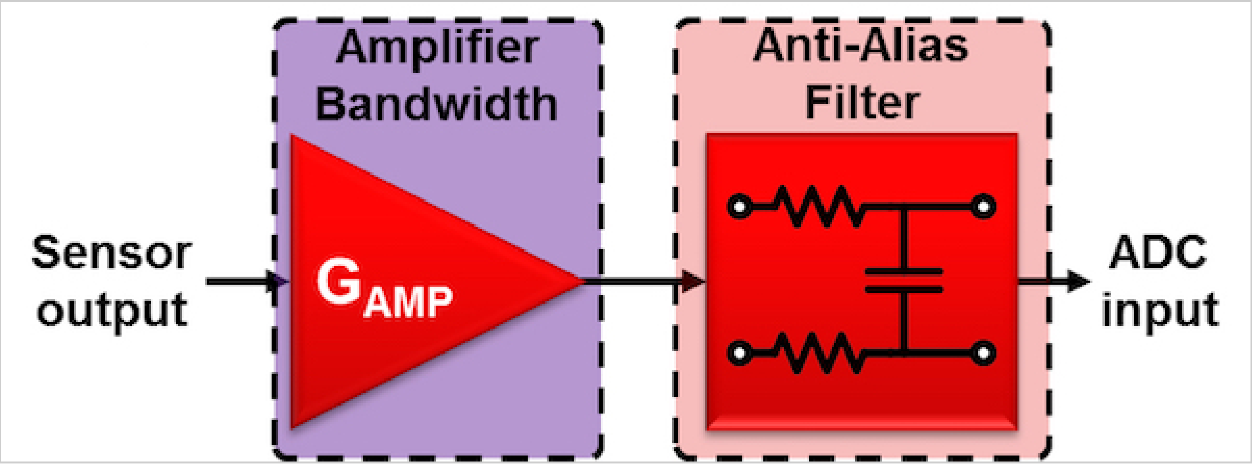

Figure 3. ADC input stage with amplifier and anti-aliasing filter

Given the condition in Equation 2, you know that the anti-aliasing filter limits the amplifier noise passing into the ADC – but how much noise does it remove? Or, more importantly, how much noise still passes through to affect the ADC and the resulting measurement? In order to calculate this, you need to look at the amplifier's noise characteristics.

Figure 4 shows an amplifier's voltage noise spectral density plot with a large 1/f region. Taken by itself, this plot tells you very little about the amplifier's actual noise contribution (highlighted in purple). In fact, the non-constant noise density – a common trait of non-chopper-stabilized amplifiers – makes it even more challenging to calculate how much noise passes to the ADC.

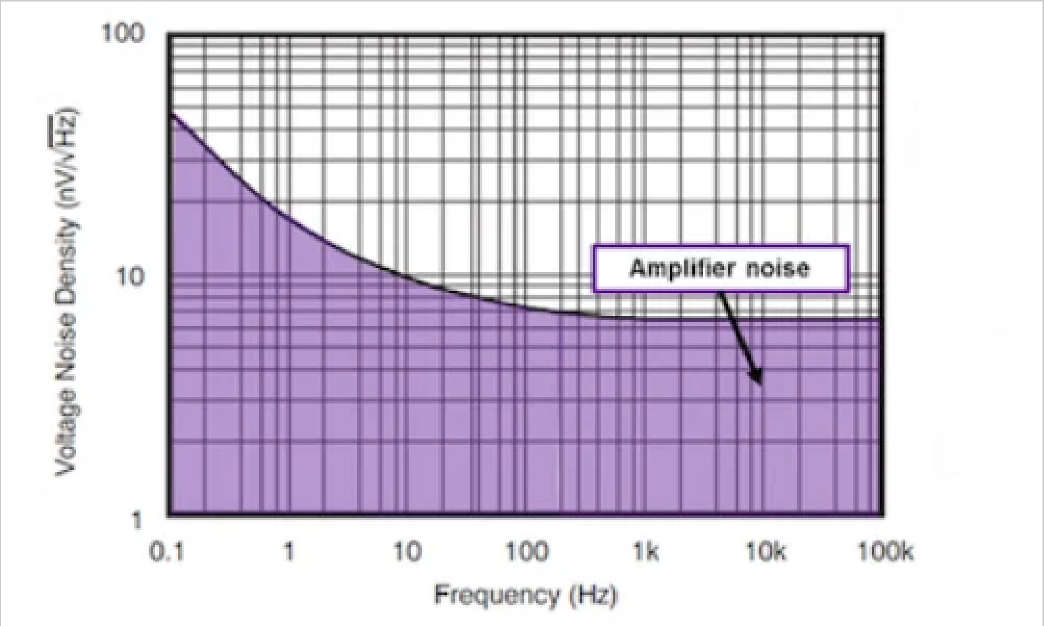

Figure 4. Generic amplifier noise density plot with a large 1/f region

To accomplish this, you need to calculate the system's ENBW. Once you've determined the ideal brick-wall filter response, you can overlay it on the amplifier's noise spectral density curve, depicted by the red region in Figure 5.

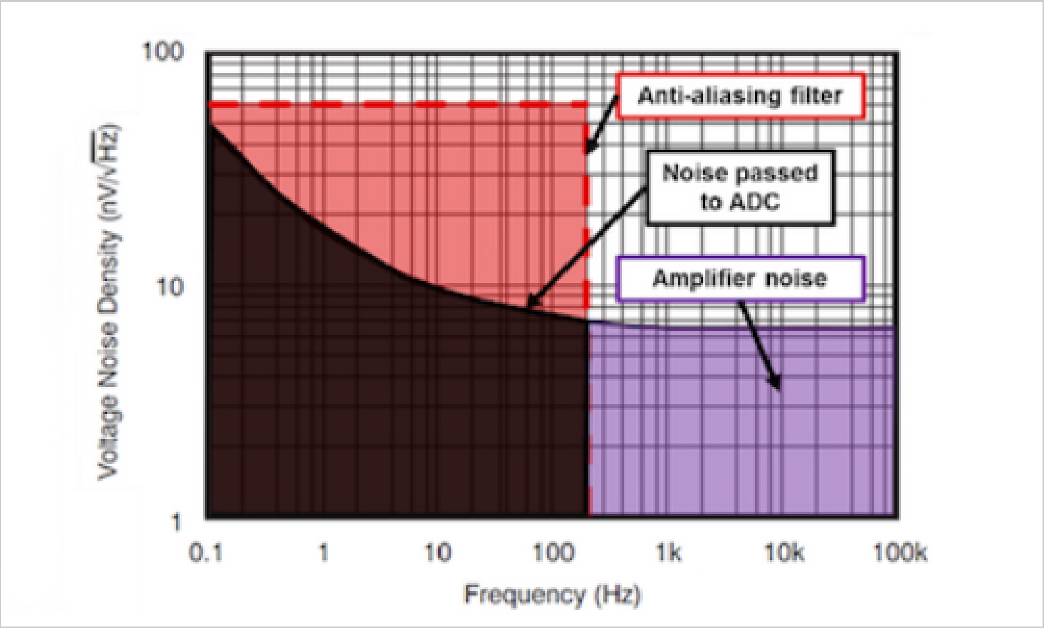

Figure 5. Amplifier noise-density plot with overlaid ENBW

The anti-aliasing filter in Figure 5 is designed such that it provides a 200Hz ENBW, effectively acting as a cutoff for the amplifier's noise. All that's left to do is calculate this noise, represented by the black area in Figure 5. When broadband noise dominates, you can use Equation 3 to calculate the root-mean-square (RMS) voltage noise:

$$V_{Noise,Broadband} = V_{Noise\ Spectral\ Density} * \sqrt{ENBW}$$

If the device has a large 1/f (flicker) noise component, similar to the amplifier shown in Figures 4 and 5, you can use direct integration or simplified formulas to calculate the device's noise contribution. TI's Precision Labs training module on amplifier noise provides more information on each of these methods.

In this case, the calculated RMS voltage noise passed to the ADC is 43.6nV$_{RMS}$.

What Contributes to ENBW?

Through this simple amplifier/anti-aliasing filter analysis, I inadvertently defined two sources that help determine a signal chain's ENBW. However, multiple filtering sources can exist in any design, and at least some filtering exists in every design. Even printed circuit boards (PCBs) that do not contain traditional filtering have trace impedances and parallel trace capacitances. These parasitics can create an unintentional RC filter, albeit one with a very large bandwidth and therefore little effect on the overall ENBW.

Figure 6 highlights the most common sources of filtering in a typical data-acquisition system: external filters such as electromagnetic interference (EMI) filters, the amplifier's bandwidth, anti-aliasing filters, digital filters of delta-sigma ADCs, and/or any post-processing filters created digitally in a microcontroller (MCU) or field-programmable gate array (FPGA). It's important to note that not all of these filtering sources appear in every signal chain. For example, many delta-sigma-based data-acquisition systems do not require post-processing filters due to the integrated filters inside these ADCs.

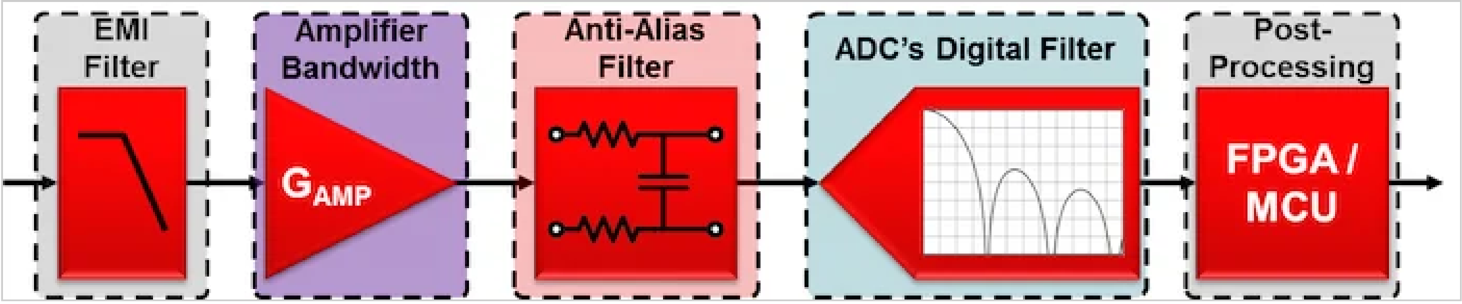

Figure 6. Common sources of filtering in delta-sigma ADC data-acquisition systems

If your signal chain has multiple filter components, you must calculate the ENBW for each component by combining all downstream filters in the signal chain. For example, to calculate the noise contribution of the amplifier in Figure 6, you would have to combine the amplifier's bandwidth with the anti-aliasing filter, the ADC's digital filter, and any post-processing filters. However, you could ignore the EMI filter.

Fortunately, even if one circuit has multiple sources of filtering, some filter types generally have a greater effect on overall ENBW than others. As a result, you may only need to calculate the ENBW for this component and ignore the other sources of filtering. For example, at lower-output data rates, the delta-sigma ADC's digital filter typically provides the narrowest bandwidth in the signal chain and therefore dominates the ENBW. Conversely, if you were to use a faster output data rate with a very wide input-signal bandwidth, the anti-aliasing filter generally limits the system's ENBW.

To learn more about ENBW, see part 5 of "Resolving the Signal," where I'll walk through a simple example to help clarify how to apply ENBW to a real-world system.

Key Takeaways

Here are important points to help better understand ENBW in delta-sigma ADCs:

- The ENBW represents an ideal brick-wall filter's cutoff frequency for a given generic filter, H(f).
- You must determine the ENBW for each noise source in the system.
- Calculate each noise source's ENBW by combining all downstream filters in the system
- The ENBW helps determine how much noise each component passes into the system.
- The ENBW is typically dominated by the filter with the smallest cutoff frequency, which is generally an anti-aliasing filter or digital filter, especially for precision delta-sigma ADCs.

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