Dithering in Analog-to-digital Conversion

Application Note

1. Introduction

High-speed ADCs today offer higher dynamic performances and every effort is made to push these state-of-the art performances through design improvements and also through innovative solutions at the system level.

For applications where the performances of the high-speed ADC in the frequency domain is the main critical parameter for the system overall performances, it is possible to improve the ADC response thanks to dither.

Dithering can be defined as adding some white noise, which has the effect of spreading low-level spectral components.

In this application note, the technique of dithering is presented, described and illustrated thanks to test results performed on the 10-bit 2.2 Gsps ADC AT84AS008 device.

2. What is Dither

To dither can be defined as adding some white noise to an analog signal destined to be digitalized. Historically, this technique has been used mainly in the audio field in order to improve the sound of digital audio.

Similarly, in the analog-to-digital conversion world, dithering can be used to enhance the dynamic range of the analog-to-digital converter.

Dithering has indeed the effect of spreading the spectral spurious contents of the signal over its spectrum.

This property is obtained thanks to the characteristics of the dither:

- Uncorrelated in time
- Uncorrelated with the analog signal
- Constant

Dither should be considered as a white random noise that has predetermined effects on the analog signal to be digitalized.

The level of this white noise should be worked out with respect to the level of noise the dither is expected to smooth out. This will be discussed in the following sections.

Note: Dithering will have both an impact on the spectral response and on the signal-to-noise ratio of the digitized signal as described in this document.

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3. How Adding Noise Can Make Things Better

At first glance, it might seem to be questionable that adding noise could improve the dynamic range of a signal.

Many attempts to explain this phenomenon was done by using some abstract examples or analogies to illustrate in a simple way how dithering can enhance a signal.

Here we have chosen a numerical analogy.

We might consider the famous Π figure. This gives a decimal figure with an infinite number of digits: 3.141592654… If one wants to keep the same precision of this value, one should keep an infinite number of digits, which would require an infinite resolution. In the real world, this is not possible and there are at least three different methods to optimize the accuracy of this figure.

The first method would be to truncate the figure to its first three decimals, leading to 3.141, but then all the information contained in the other digits is definitely lost.

The second method would be to round the value but then a decision should be made between 3.141 and 3.142… and in both cases, the result is not correct and will be conveying the same error at each attempt (arbitrary result).

Finally, a trade-off can be reached by adding a random figure to the last digit that cannot be taken into account:

$$3{\cdot}1415 + 0{\cdot}000X = 3{\cdot}14Z$$

Where Z could be a two with the same statistical probability: it might be sometimes one or some other times two.

On average, the fourth digit which cannot be taken into account because of lack of accuracy is contained in the averaged figure. On 100 attempts, the probability to have 3.141 is half and the probability to have 3.142 is also half, which gives on average :

$(50 \times 3.141 + 50 \times 3.142)/100 = 3.1415$

The decision to make the third digit a one or a two is non-deterministic, on the contrary to the two first methods where it is arbitrary. Of course, when you consider Π changing from 3.141 to 3.142 at every new attempt, there is some kind of blur around the figure, which can be associated to the noise which is added in dithering. Dithering adds a little noise but allows for a significant reduction in distortion.

The following sections describe primarily why dither can be of benefit in analog-to-digital conversion and secondly it gives more details on the effects of dithering in analog-to-digital conversion.

4. Why Is Dithering Needed In Analog-to-Digital Conversion

Because the resolution of an ADC cannot be extended to the infinite (only a fixed number of bits can be used to represent a sample), only a limited dynamic range can be achieved as well as a limited accuracy (*finite word length effect*).

A 16-bit ADC should ideally yield -96 dB dynamic range, unfortunately, in the real world, this – 96 dB dynamic range may decrease to even –80 dB because of quantization noise. This phenomenon is even more accentuated when dealing with broadband data converters, where the bandwidth is of the order of the GHz (the AT84AS008 10-bit 2.2 Gsps ADC has a 3.3Hz bandwidth at –3 dB). The wider the band the ADC can operate in, the more thermal noise is integrated and the more the dynamic range of the ADC is impacted.

As the demand for both linearity and bandwidth increases, a physical limit is being reached and only a trade-off between the bandwidth and the dynamic range can be considered. This explains especially why high resolution ADCs (above 12 bits) are not capable today of achieving GHz speeds and GHz bands: as the resolution increases, only lower speeds can be operated to achieve high dynamic performances.

On the other hand, with a lower number of bits (8 or even 10 bits), higher speeds can be achieved but with lower dynamic performances. In order to increase the dynamic range of an ADC up to (or as close as possible to) its ideal value, dither can be used to spread out the spectral low-level contents of the signal (short-term errors due to the INL pattern of the ADC) across the spectrum as broadband noise.

If –96 dB are really needed in practice, it would be necessary to use a 17-bit or even an 18-bit resolution ADC. As an example, the AT84AS008 10-bit 2.2 Gsps ADC should yield a theoretical dynamic range of about –58 dB. Although its SFDR (Spurious Free Dynamic range) is about –58 dBc at 1.7 Gsps / 710 MHz –1 dBFS signal, this figure decreases as the sampling rate and input frequency increase and also as the analog input power level decreases.

For a given couple of sampling frequency and analog input frequency, the SFDR figure linearly decreases with the analog input power level. As the amplitude of the fundamental decreases, it gets closer to the noise floor and also to the low-level spurious contents of the spectrum.

Dithering could then be used to attenuate the effect of decreasing the input power level or increasing the sampling and input frequencies. The effects of dither on the ADC performances are described in section Section 5. on page 4.

5. What Are the Effects of Adding Dither to High-speed ADCs

The advantage of adding dither is to smooth the spectrum of the signal out, this impacts directly the SFDR performance of the ADC and the experiments show that an improvement of about 5 dB can be achieved by adding dither to the ADC input.

Figure 5-1. Signal Spectrum with No Dither (Fs = 1.7 Gsps and Fin = 710 MHz, –5 dBm)

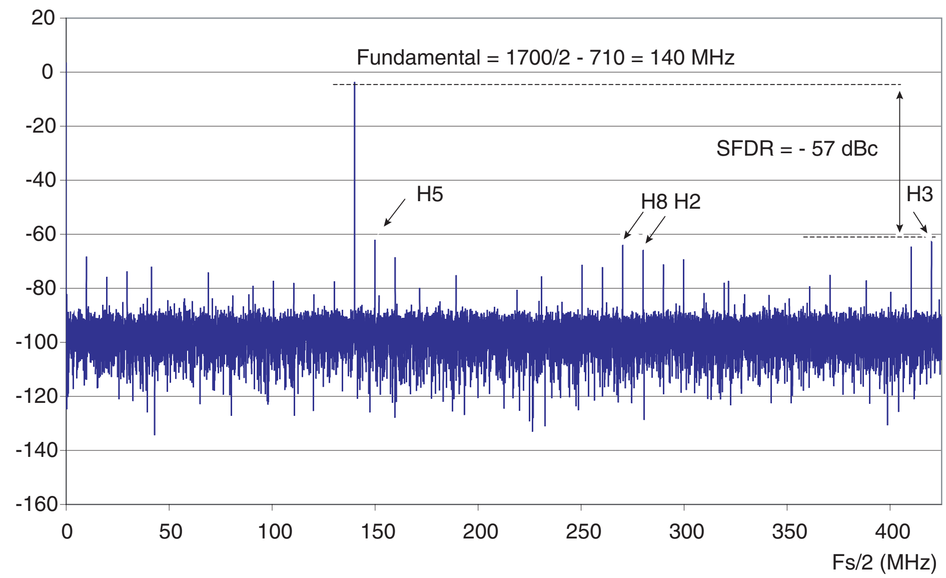
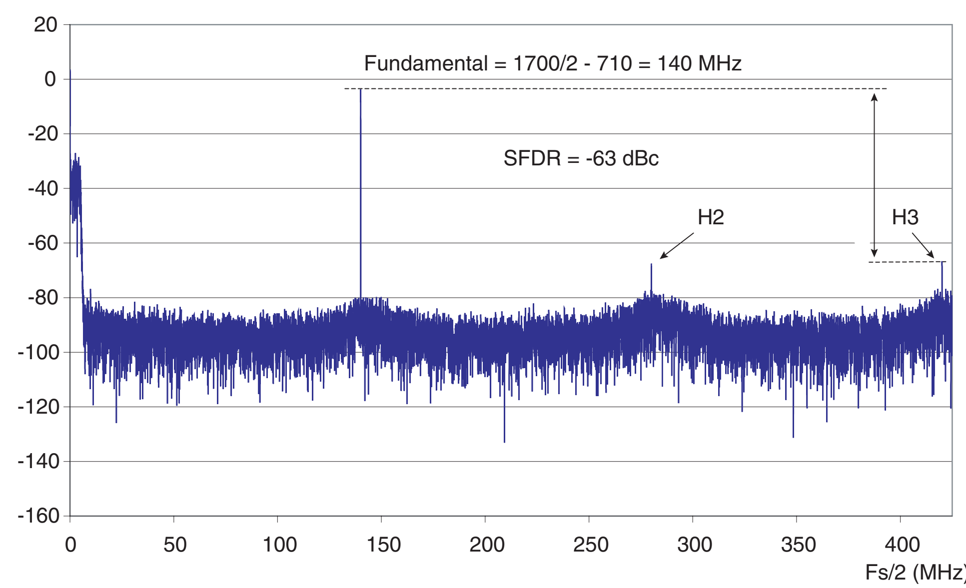


Figure 5-2. Signal Spectrum with –17 dBm Added Dither Noise (Fs = 1.7 Gsps Fin = 710 MHz, –5 dBm)



In Figure 5-1 on page 4 and Figure 5-2 on page 4 illustrated above, we see the two main effects of adding dither noise to the ADC input:

- The spectrum with dither shows a noise floor below 85 dB while the spectrum without dither has a noise floor below 90 dB.
- Most of the harmonics in the spectrum with dither have been smoothed out (except for H2 and H3, whose level has however decreased significantly).

In this particular case (Fs = 1.7 Gsps Fin = 710 MHz, Pin = –5 dBm, Pdither = –17 dBm), the SFDR increases by 6 dB compared to the SFDR without dither and the spectrum has been cleaned out from most of the harmonics and spurious components.

However, the spectrum shows a cone under each tone (under the fundamental and H2), which is due to the saturation of the analog input due to the addition of dither noise.

To avoid this saturation and therefore this kind of spectral shape, it is necessary to reduce the dither noise level, as shown in Figure 5-3 but then the SFDR will not be optimum.

Figure 5-3. Signal Spectrum with –25 dBm Added Dither Noise (Fs = 1.7 Gsps, Fin = 710 MHz, –5 dBm)

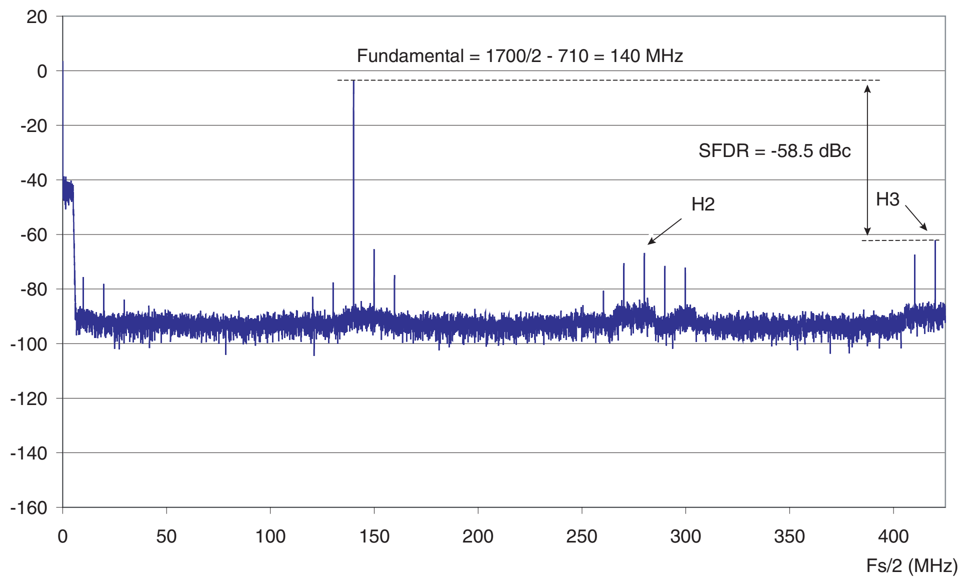


Figure 5-4. Signal Spectrum with No Dither Noise (Fs = 1.7 Gsps Fin = 710 MHz, –20 dBm)

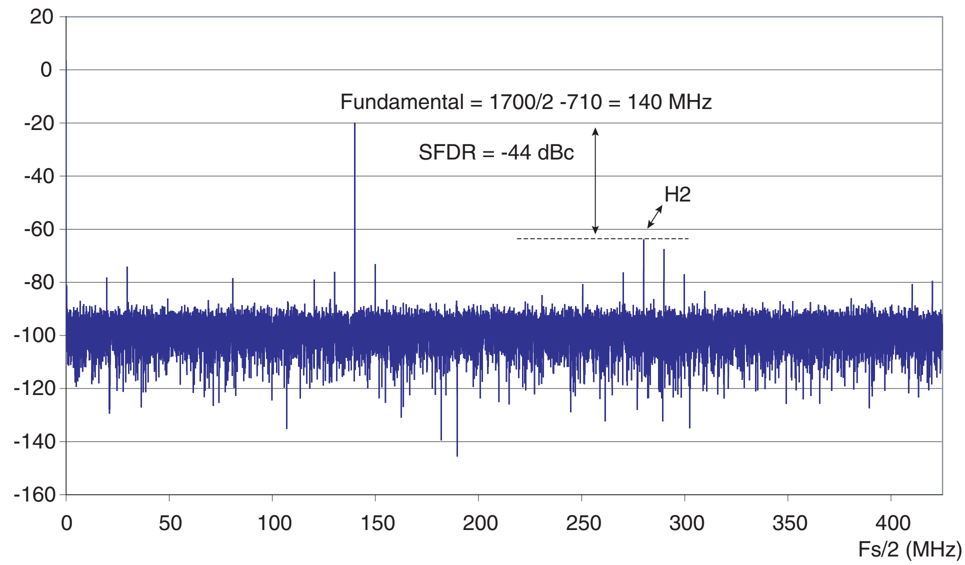
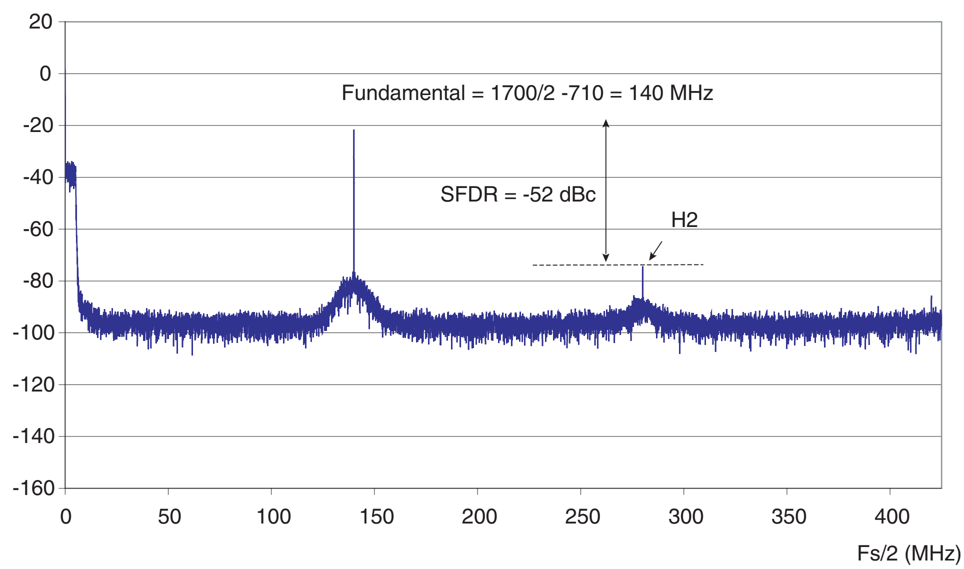


Figure 5-5. Signal Spectrum with –17 dBm Added Dither Noise (Fs = 1.7 Gsps Fin = 710 MHz, –20 dBm)



As shown in Figure 5-4 and Figure 5-5, the effect of dither on the spectrum is clear: all the spurs (dependent and independent) have been cleaned out except for H2 which remains and defines the SFDR parameter. In this particular case (Fs = 1.7 Gsps Fin = 710 MHz, Pin = –20 dBm, Pdither = –17 dBm), the SFDR increases by 8 dB.

Again, the analog input saturates, leading to this spectral shape with the cones under each tone but again also, adding dither is a question of compromise between the spectral purity to be achieved and the increase in signal-to-noise ratio.

Figure 5-6. Signal Spectrum with No Dither Noise (Fs = 1.7 Gsps Fin = 710 MHz, –45 dBm)

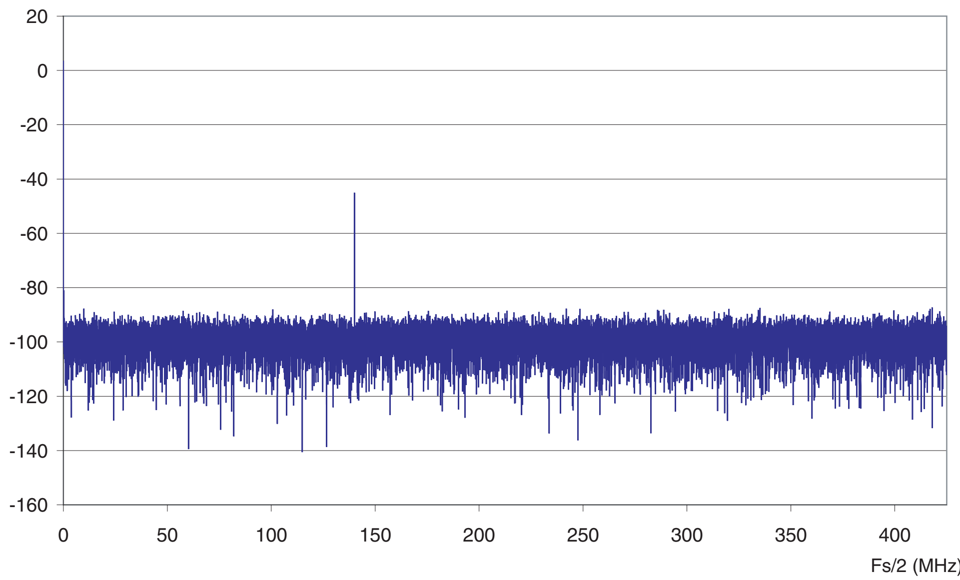
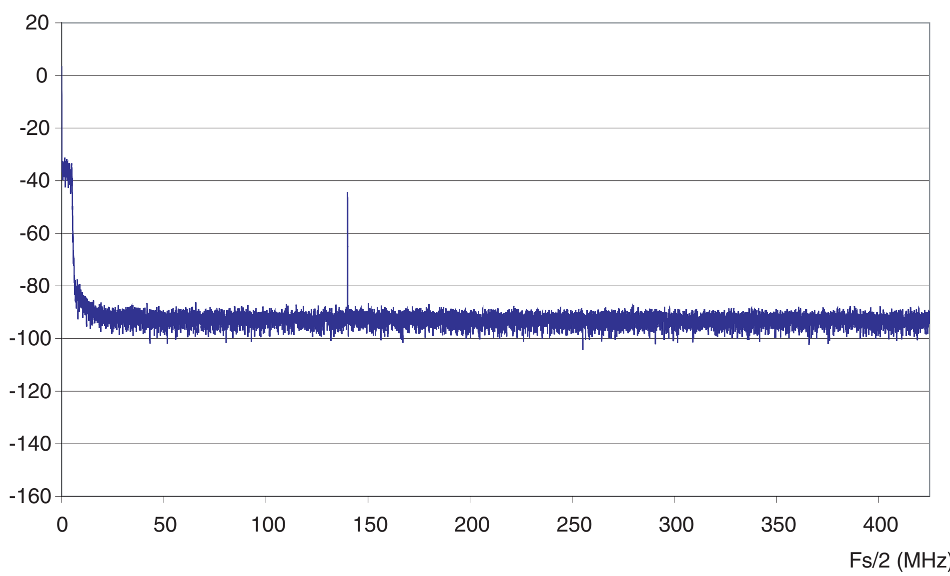


Figure 5-7. Signal Spectrum with –17 dBm Added Dither (Fs = 1.7 Gsps Fin = 710 MHz, –45 dBm)



In Figure 5-6 and Figure 5-7, the dither has no additional effect on the performance of the ADC: the SFDR and SNR of the signal with and without dither are equivalent.

As shown in Figure 5-7 on page 7, adding dither also increases the noise density and consequently affects the SNR (Signal to Noise Ratio) figure of the ADC by some dB (for a 10 dB gain in SFDR, the SNR might decrease by 3 dB).

Table 5-1. SFDR, SNR and THD Figures with and without Dither Noise (Fs = 1.7 Gsps, Fin = 710 MHz)

	Input Power (dBm)	Without Dither	With Dither (–17 dBm)	Difference (with/without)
|SFDR|	–5 dBm	57 dBc	63 dBc	6 dB
	–20 dBm	44 dBc	52 dBc	8 dB
SNR	–5 dBm	49 dBc	46.8 dBc	–2.2 dB
	–20 dBm	34 dBc	31 dBc	–3 dB
|THD|	–5 dBm	52 dBc	59.5 dBc	7.5 dB
	–20 dBm	41 dBc	50 dBc	9 dB

The trade-off between the gain in SFDR and the little loss in SNR can be found by optimizing the level of dither noise to be added. For ADCs, the level of dither is usually calculated with regards to the level of the INL (Integral Non Linearity) pattern. To smooth out the integral non linearity of the ADC, the dither has to be wider than the INL pattern but not too wide as to avoid a sharp decrease of the SNR figure.

Figure 5-8. SFDR and SNR Versus Dither Level (10-bit 2.2 Gsps ADC, –7 dBm Analog Input, DC to 5 MHz Out-of-band Dither)

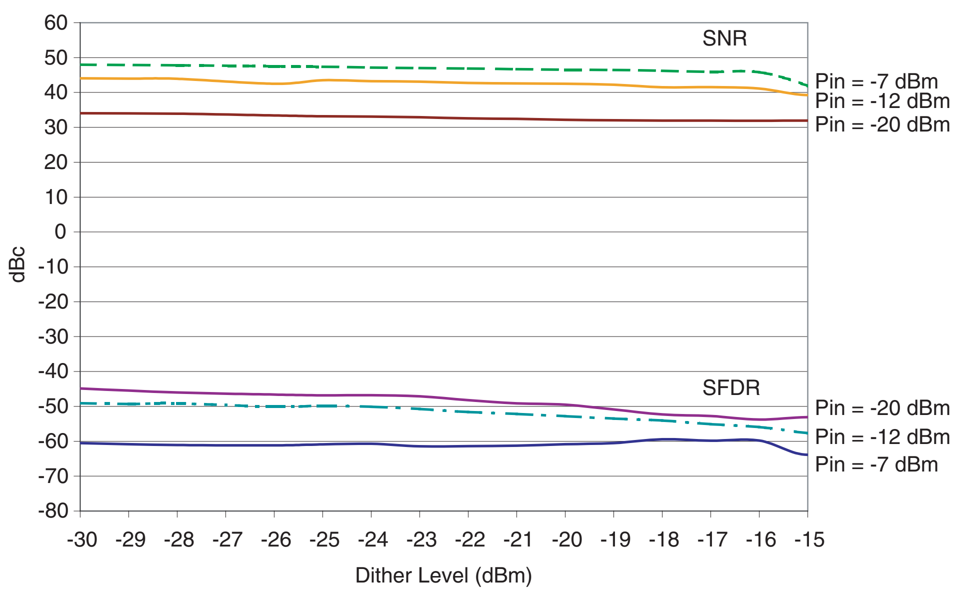
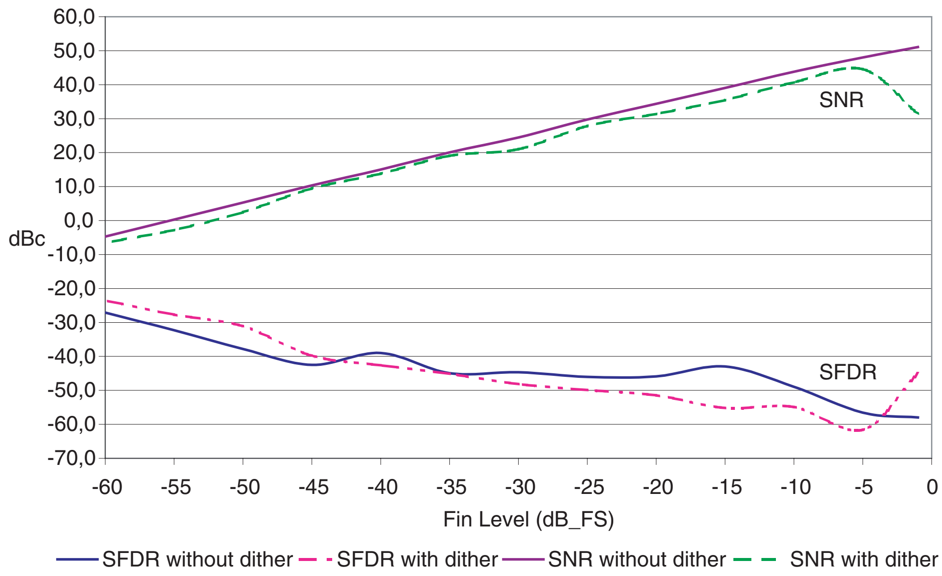


Figure 5-8 on page 8 shows the influence of the level of the added dither to the performances of the ADC (SNR and SFDR) for three different analog input levels. These curves show that the dither level should be chosen for this ADC in the –25 to –17 dBm range to obtain an equivalent effect of the dither on the SNR and SFDR parameters.

Figure 5-9. SNR Versus Input Power Level with And Without Dither at Fs = 1.7 Gsps / 710 MHz (AT84AS008 10-bit 2.2Gsps ADC, –17dBm DC to 5 MHz Out-of-band Dither)



In Figure 5-9, we can see that an optimum in the SFDR is reached for –17 dBm dither and an analog input level of about –15 dBFS (–16 dBm) parameter.

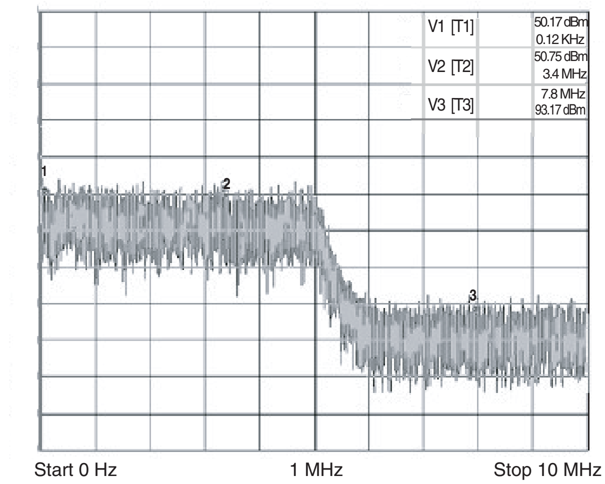
Although it is possible to increase the SFDR parameter by about 3 dB to even 12 dB, you can also see that the SNR will not vary a lot. Depending on the end application, adding dither can thus be very interesting.

6. Noise Shaping

Noise shaping is also a technique which can be used to optimize the effects of dithering on the ADC performances. As the signal of interest only occupies a given part of the spectrum, it might not be necessary to add dither to all the spectrum but only to a specific band of it, so that the bulk of the noise is only added to the part of the spectrum which is not of interest.

In the AT84AS008 10-bit 2.2 Gsps ADC example, dither was added only from DC to 5 MHz so that it was out-of-the band of interest for the signal to be processed. This out-of-band noise needs of course to be removed in the post processing of the ADC output signal but since the ADC output is digital, this can be easily done through software thanks to a digital filter.

Figure 6-1. –22 dBrms, DC to 5 MHz Out-of-band Dither Curve



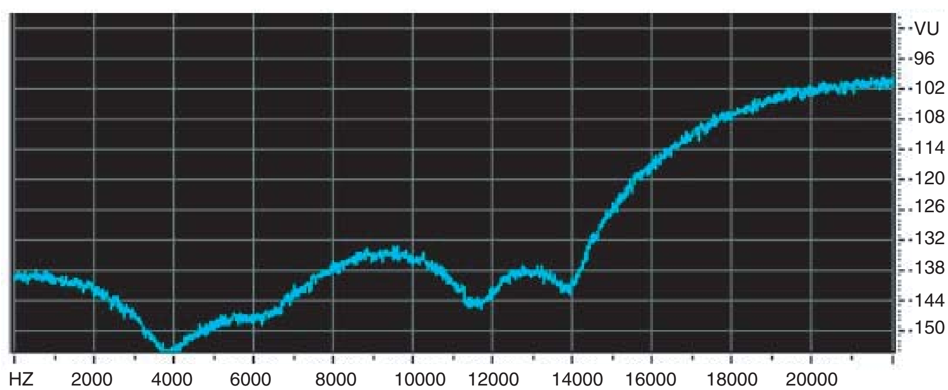
Going back to audio signals, the noise is added to the part of the spectrum where it will affect the listening the least which, is the high frequencies.

The noise-shaping technique used on the 10-bit 2.2 Gsps ADC can be qualified as very basic technique (low pass filtered noise). Other very sophisticated noise shaping techniques have indeed been devised, mainly by audio engineers, who were the first to work on this topic.

High-order filters are then used to shape very accurately noise to match the exact portion of the spectrum where the ear is sensitive.

One known noise-shaping curves for audio signals is given below (by Steinberg):

Figure 6-2. Noise-shaping Curve Integrated into WaveLab Audio System (By Steinberg)



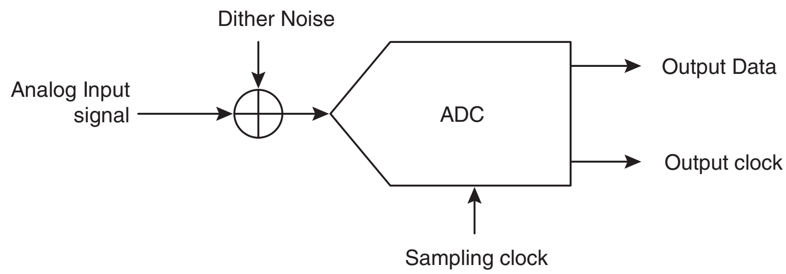
7. How Dither Can Be Added to the ADC

In the previous sections, we have seen what the effects of dither were on the dynamic range of a high-speed ADC such as the 10-bit 2.2 Gsps ADC AT84AS008.

Now that everyone is convinced of the benefits of using dither in analog-to-digital conversion, the following section gives the principle of adding external dither to an analog-to-digital converter.

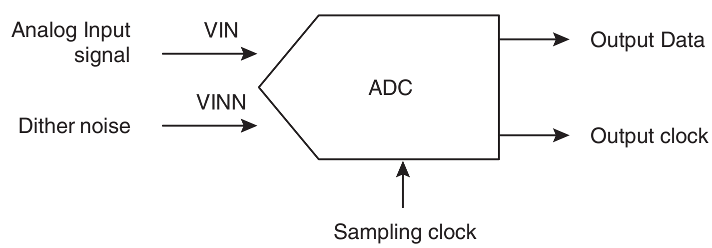
The principle of operation is illustrated in Figure 7-1.

Figure 7-1. Applying Dither to an ADC, Simplified Block Diagram



As most of e2v Broadband Analog-to-digital converters accept differential analog inputs, this diagram becomes:

Figure 7-2. Applying Dither to an ADC with Differential Analog Input



This diagram can be detailed considering the need of an anti-aliasing filter on the analog input path and a filter for noise-shaping considerations on the dither path.

In the case of the 10-bit 2.2 Gsps ADC, a low pass filtering with a cut-off frequency of 5 MHz was used.

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