Improving Resolution of SAR ADC

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ABSTRACT

Real world parameters such as temperature, light intensity, and others are continuous in time and infinite in resolution. For digital processing, the analog signal must be converted to a digital code of fixed length, by process called 'quantization', at discrete time intervals, by a process called 'sampling'. This quantization error sets the threshold beyond which the analog-to-digital converter (ADC) cannot distinguish or resolve the signal anymore. Hence, this is the noise level of an ideal ADC determined by the resolution of conversion.

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1 Introduction

Let the least significant bit (LSB) be q, and resolution of the system be (N). RMS value of the noise due to the quantization error is expressed by:

$$V_n = q / \sqrt{12}$$

Noise exists in a band from 0 to fs/2 where fs = sample rate. Assume a voltage swing of a sine wave with a peak to peak value of V.

$$Vrms = V / 2\sqrt{2}$$

$$Also, V = 2^N * q$$

$$Vrms = 2^N * q / 2\sqrt{2}$$

$$SNR = 20 \log \left(Vrms / Vn \right)$$

$$SNR = 20 \log \left(2^N * q * \sqrt{12} / 2\sqrt{2} * q \right)$$

$$SNR = 20 \log 2^N + 20 \log \sqrt{6} / 2$$

$$SNR = 6.02N + 1.76\ dB$$

This is the theoretical dynamic range, also known as SNR, achievable from a N-bit ADC.

ADCs are implemented in semiconductor process using passive and active elements depending on the conversion algorithm. These practical implementation blocks introduce other sources of noise such as thermal noise, flicker noise, and so forth. Hence, in a practical ADC the dynamic range is lesser than what is theoretically achievable.

A measure of the resolution of ADC with all the noise sources accounted for is effective-number-of-bits (ENOB).

Reworking,

(SNR_{actual} – 1.76)/6.02 = N effective

Where N is effective number of bits or ENOB supported by the ADC.

1.1 Relevance of Nyquist Sampling Theory

In a text-book ADC process, if the analog signal is sampled at frequency Fs, then all of the converted frequency components will be represented in the 0 to Fs/2 frequency domain.

This is a very relevant concept for noise in the system. Noise sources such as quantization noise and thermal noise are wide-band in nature that is they are present at all frequencies. In a sampled spectrum, the total energy of such wide-band noise sources remains constant, but gets evenly distributed over the 0 to Fs/2 frequency band. Hence, the dynamic range, or SNR, of the ADC is independent of the conversion speed. For example, ADS8920B (1-MHz ADC), ADS8922B (500-kHz ADC) and ADS8924B (250-kHz ADC) all have the same SNR performance of 96-dB.

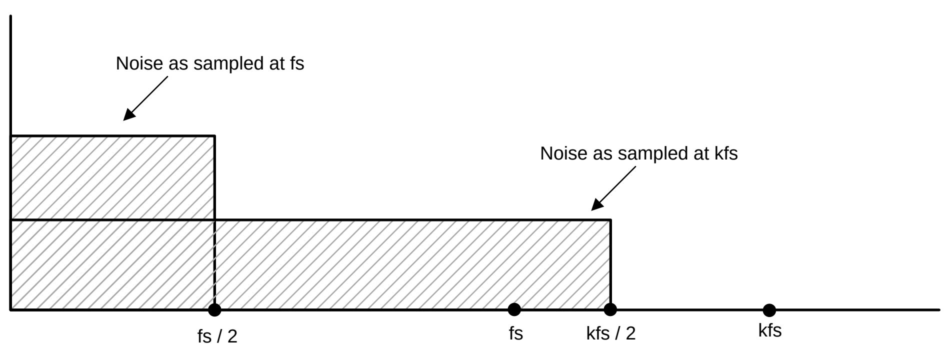

Figure 1. Frequency Spectrum of ADC Oversampled K Times

This shows whether the ADC is operated slower or faster, while keeping everything else same, the dynamic range will not be affected.

As the noise energy in the ADC remains the same with respected to conversion speed, a faster ADC would have lower noise density per frequency bin as compared to a lower speed counterpart. If the signal frequency of interest Fm is lesser than Fs/2, then the excess portion of frequency spectrum, that is, Fm < Fexcess < Fs/2 can be filtered. The ADC noise energy in this filtered spectrum will be eliminated and this results in improved resolution in the 0 to Fm frequency range.

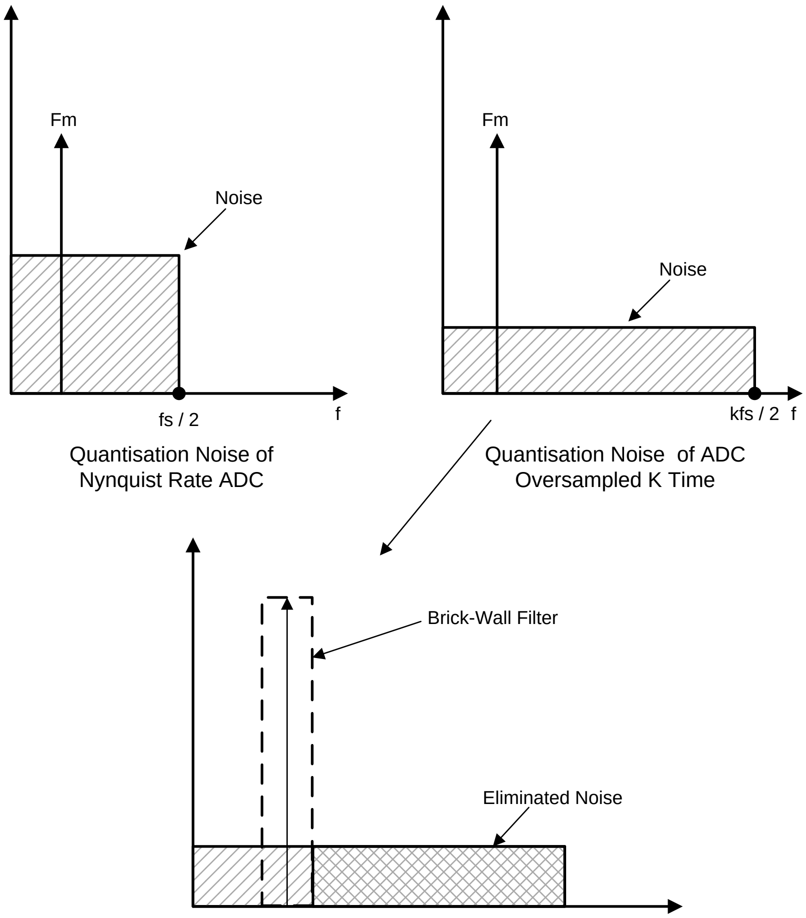

Figure 2. Digital Filtering to Reduce the Noise After Oversampling

Various digital filters can be implemented to attenuate the excess frequency spectrum with different combination of complexity and efficacy.

The over sampling ratio can be expressed as:

$$OSR = \frac{F_S}{2 \times F_m}$$

By Nyquist sampling theory, Fs > 2 x Fm which results in an OSR = 1. Improvement in resolution due to over sampling and filtering can be estimated as:

SNR = 6.02 N + 1.76 + 10 log (OSR)

Using the above equation, it is also evident that OSR = 4 results in:

SNR = 6.02 N + 1.76 + 6.02

which is the same as:

SNR = 6.02 (N + 1) + 1.76

The results from the above equation show that OSR of 4 results in 1-bit of extra resolution.

It is important to note that the above information holds true if the digital filter used for chopping off the noise spectrum is ideal, that is, a brick-wall filter. Over sampling and filtering can help reduce uncorrelated noise sources that are random and wide band. It will not have any effect on noise sources that are correlated, deterministic and at specific frequency bands.

1.2 Oversampling and Decimation Improves Resolution

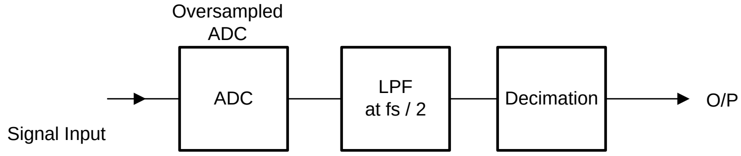

Figure 3. Stages Involved in Analog to Digital Conversion With Oversampling and Decimation

Decimation involves picking every k^{th} sample where K = OSR.

1.3 Comparison of Delta Sigma vs SAR ADC

Table 1. Comparison of Delta Sigma vs SAR ADC

DEVICE	ADS8900B – TI SAR ADC	ADS127L01- TI Delta Sigma
Type	SAR	Sigma Delta
F-Sample	1 MSPS	512 KSPS
N	20	24
SNR_best	104.5dB	105 dB at 512 KSPS

Case 1

Operating frequency of 100 KHz

$f_s \geq 2f_m$

$f_s \geq 200$ KHz

1.3.1 ENOB Delta Sigma

N = (SNR – 1.76) / 6.02

N = (105 – 1.76) / 6.02

N = 17.2

1.3.2 ENOB SAR

N = (SNR – 1.76) / 6.02

N = (104.5 – 1.76) / 6.02

N = 17

Table 2. Comparison of SAR ADC vs Delta Sigma ADC - Without Oversampling

ADC Parameters	SAR	SIGMA DELTA
ENOB	17	17.2
BITS	20	24
SNR	104.5 dB	105 dB

The effective number of bits of both devices are close.

1.4 With Oversampling

1.4.1 Case 1: Operating Frequency of 100 KHz

$f_s \geq 2f_m$

$f_s \geq 200$ KHz

$OSR = f_{os}/2*f_m = 1$ MHz / 200 = 5, $f_m = 100$ KHz

SNR = 6.02 N + 1.76 + 10 log OSR

With N = 17

SNR = 6.02 ×17 + 1.76 + 10 log 5

SNR = 111.13

N = (SNR – 1.76) / 6.02 = (111.13 – 1.76) / 6.02

N = 18.1

Table 3. Comparison of SAR ADC vs Delta Sigma ADC - For 100 KHz, With Oversampling and Decimation

ADC Parameters	SAR	SIGMA DELTA
ENOB	18.1	17.2
BITS	20	24
SNR	111.13 dB	105 dB

1.4.2 Case 2: Operating Frequency of 20 KHz:

$f_s \geq 2f_m$

$f_s \geq 40$ KHz

$OSR = f_s/2f_m = 1$ MHz / 40 = 25, $f_m = 20$ KHz

SNR = 6.02 N + 1.76 + 10 log OSR

= 6.02 × 17 + 1.76 + 10 log 25

SNR = 118.07

N_{eff} = (SNR – 1.76)/6.02

= (118.07 – 1.76) / 6.02 = 19.03

1.4.2.1 Sigma Delta

N_{eff} = (SNR – 1.76)/6.02

= (105 – 1.76) / 6.02 = 17.2

Table 4. Comparison of SAR ADC vs Delta Sigma - for 20 KHz, Sampling With Oversampling and Decimation

ADC Parameters	SAR	SIGMA DELTA
ENOB	19.03	17.2
BITS	20	24
SNR	118.07 dB	105 dB

NOTE: OS is done inside the Delta Sigma converter.

1.4.3 Case 3: Using TI ADS9110

Table 5. Using 2 MSPS ADS9110

F_{samp}	2MSPS
N	18
SNR_{best}	100 dB

1.4.3.1 Operation at 100 KHz

OSR = 2 M / 200 KHz = 10

$$N_{eff} = \frac{(100\,dB - 1.76)}{6.02} = 16.3 \quad (1)$$

SNR = 6.02 ×16.3+1.76+ 10 log 10

SNR = 109.86

N = SNR – 1.76 / 6.02 = 17.8

1.4.3.2 Operation at 20 KHz

OSR = 2M / 40 KHz = 50

SNR = 6.02 ×16.3+10 log 50

6.02 × 16.3 + 16.98

SNR = 115.06

N = (SNR – 1.76) / 6.02 = 18.8

Table 6. Comparison of 2 MSPS SAR ADC With Delta Sigma ADC – for 20 KHz and 100 KHz With Oversampling and Decimation

ADC Parameters	SIGMA DELTA	SAR @20 KHz	SAR @100 KHz
ENOB	17.2	18.8	17.8
BITS	24	18	18
SNR	105	115.06	109.86

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