THE EFFECTIVE NUMBER OF BITS (ENOB) FOR R&S®RTO6 OSCILLOSCOPES

White paper | Version 01.00

ROHDE&SCHWARZ

Make ideas real

CONTENTS

This white paper provides an introduction to the signal quality parameter effective number of bits (ENOB) and shows measured values for R&S®RTO6 oscilloscopes.

ENOB BASICS

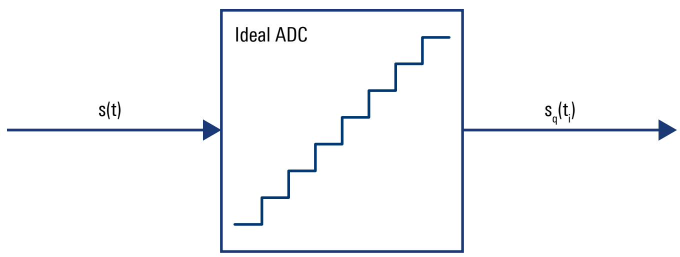
The effective number of bits (ENOB) quantifies the quality of analog-to-digital conversions. A higher ENOB means that voltage levels recorded in an analog-to-digital conversion are more accurate.

In an oscilloscope, the ENOB is determined by the quality of the analog-to-digital converter and the instrument as a whole. This white paper explains how to measure the ENOB for oscilloscopes and shows results for an R&S®RTO6 oscilloscope.

Analog-to-digital converters and ENOB

A simple schematic of an ideal analog-to-digital converter (ADC) is shown in Fig. 1.

Fig. 1: Schematic of an ideal ADC



The ideal ADC is perfectly linear and simply quantizes the incoming signal. The process of quantization inevitably introduces quantization noise. Using the signal power and the noise power, it is possible to derive a signal-to-noise ratio (SNR) for the signal after analog to digital conversion. Using a full-scale sine wave as input, the SNR can be expressed as:

Equation 1: $$SNR = 1.5 \times 2^{2B}.$$

The term B denotes the number of bits of the ADC. Expressing the equation in dB results in:

Equation 2: $$SNR_{dB} \approx 1.76 + 6.02B \text{ dB}.$$

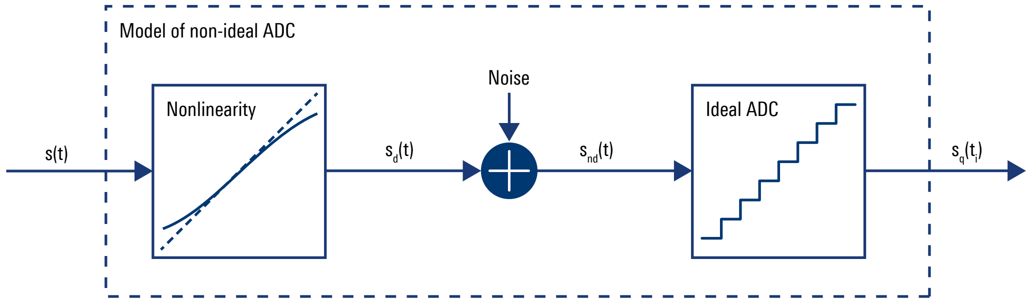
Re-arranging the equation to solve for B results in:

Equation 3: $$B \approx \frac{SNR^{dB} 1.76}{6.02}$$

This equation shows how the number of bits can be derived from the SNR and gives the basis for calculating ENOB.

Ideal ADCs do not exist. In addition to quantization noise, every ADC adds additional distortions to the input signal. Typical distortions are noise, a nonlinear input characteristic, along with gain and offset errors. A model for a non-ideal ADC is shown in Fig. 2.

Fig. 2: A model of a non-ideal ADC



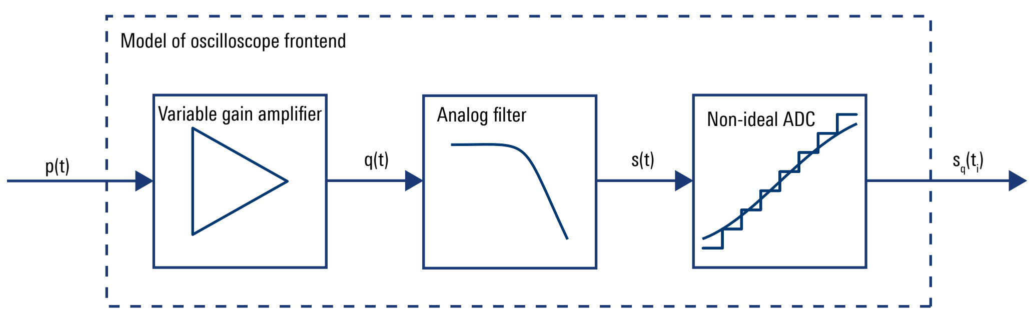
Noise directly degrades the SNR for the ADC. Nonlinearities generate harmonics which reduce the potential SNR. A 12-bit ADC might specify an ENOB of 10.5. Even though the ADC outputs 12 bit, the achievable SNR corresponds to that of an ideal ADC with 10.5 bit.

The ENOB also depends on the input frequency. High frequencies may result in greater nonlinearities within a circuit and further degrade the ENOB. So, users need to know ENOB relative to the input signal frequency.

Oscilloscope frontend

In an oscilloscope, additional elements are required prior to the ADC. The elements are presented schematically in Fig. 3. The first is a variable gain amplifier (VGA), which scales the oscilloscope input signal for optimum ADC dynamic range usage. The second is a lowpass anti-aliasing filter. Both introduce further distortions to the input signals. The VGA has active components and introduces nonlinearities while also maintaining frequency dependent behavior. The analog filter also has a non-ideal frequency response. A good frontend design minimizes distortion and/or noise added to the input signal.

Fig. 3: A simplified model of an oscilloscope frontend



Measuring ENOB

The IEEE has defined terminology and test methods for analog-to-digital converters (IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters, IEEE Standard 1241-2010) that includes a formula for quantifying the ENOB:

Equation 4: $$\mathrm{ENOB} = 0.5\log2(\mathrm{SINAD})\ 0.5\log_2(1.5) - \log_2 (A/V)$$

V = full-scale voltage range of the device under test
A = peak-to-peak amplitude of the sine wave fitted to the output
SINAD = signal to noise and distortion ratio

Equation 5: $$SINAD = \left(P_S/P_{NAD}\right)$$

P_S = signal power; power in the FFT bin corresponding to the input frequency
P_{NAD} = noise and distortion power;
sum of powers in all other frequency bins excluding the 0-frequency bin, up to and including the bin at Nyquist frequency

Note: SNR and SINAD, as defined in IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters, IEEE Standard 1241-2010, are ratios of root mean square (RMS) values and not a ratio of power values as is typical in communications engineering.

Choice of amplitude

The IEEE standard does not specify a particular input amplitude for ENOB measurements and any input amplitude can be used. ENOB measurements help compare different systems but can only be used as a reference when the input amplitude for the measurement is included.

50 mV/div is a common user digital signal scaling for oscilloscopes. Specifications often communicate ENOB values taken at 50 mV/div when the full-scale value is 500 mV for instruments with 10 vertical divisions.

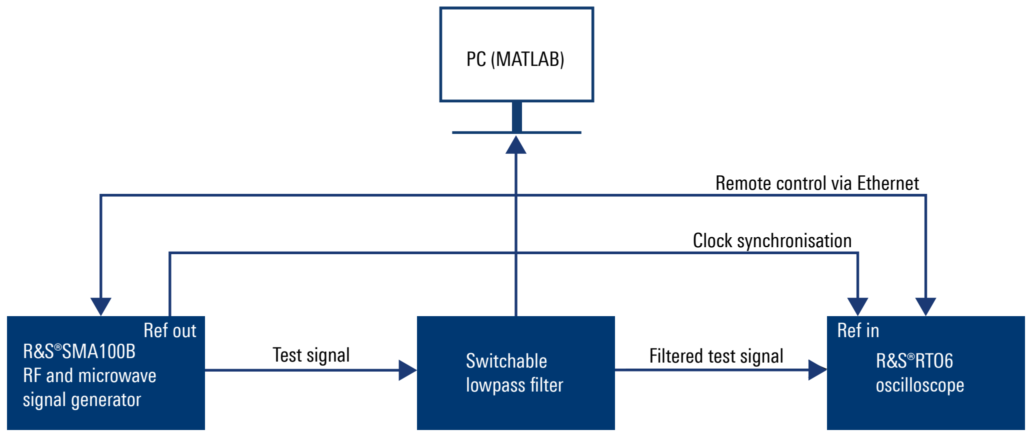
Choice of frequency

The input frequency must fit exactly onto a FFT frequency bin. The sampled sequence should include only whole periods of the test signal. Any windowing effects which would make the measurement unnecessarily complicated need to be avoided. Reliable measurements need the input signal to sample as many phases as possible.

TEST SETUP AND MEASUREMENT RESULTS

Fig. 4 is a schematic presentation of the equipment setup. An R&S®SMA100B RF and microwave signal generator provide the test signal. To reduce the effects of signal generator harmonics in ENOB measurements, the R&S®SMA100B output is filtered with an analog lowpass filter. The device under test is the next instrument in the measurement chain, which here is an R&S®RTO6 oscilloscope. High quality cables should be used for transferring signals between the instruments since these can also be a source of distortion. A PC running a MATLAB program remotely controls the instruments and while also reading and evaluating acquisition data from the R&S®RTO6.

Fig. 4: Test equipment setup



Oscilloscope settings

The R&S®RTO6 has a sampling rate of 10 Gsample/s (no decimation or interpolation) which corresponds to a resolution of 100 ps. Vertical scaling is set to 50 mV/div, 500 mV full scale. Input coupling is set to 50 Ω and filters are applied that correspond to the measurement bandwidth.

Remote control

Remote control ensures that ENOB measurement testing can be automated and repeated over multiple frequencies, oscilloscope settings and oscilloscope models. The R&S®RTO6 supports different remote-control methods, including Python, MATLAB and SCPI.

The R&S®SMA100B output level depends on the output frequency. The lowpass filter is also not ripple free and the oscilloscope has its own amplitude frequency response. Using a script for remote control, the output amplitude of the R&S®SMA100B adjusts to the percent full scale value desired for each test frequency. Oscilloscope users typically scale waveforms to 80 % full screen, although 90 % is also possible.

Results

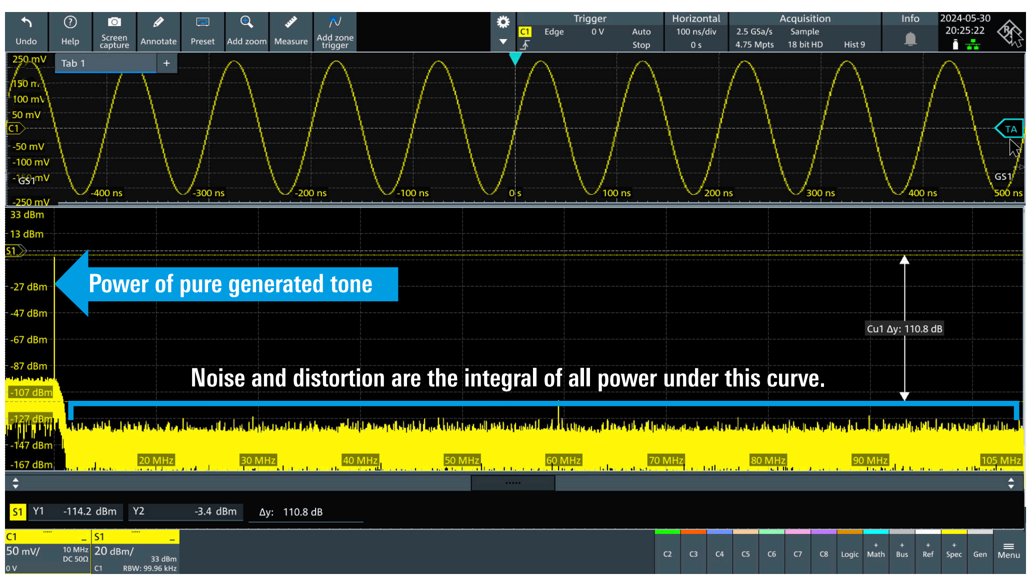
R&S®RTO6	Measured ENOB
50 MHz	9.4
100 MHz	9.0
200 MHz	8.6
300 MHz	8.2
500 MHz	8.1
1 GHz	7.7
2 GHz	7.1
4 GHz	6.0
6 GHz	6.1

Measured at 50 Ω, 50 mV/div, filters, 10 MHz input signal with 90 % full-scale.

Frequency domain ENOB calculations

ENOB results can also be obtained using the FFT functionality of the R&S®RTO6. The ratio of the power in the generated tone is compared to power in all harmonics plus broadband noise.

Fig. 5: The top of the image shows a pure sinewave from the generator captured by the oscilloscope. The bottom of the image shows the equivalent FFT.



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