

# DESIGN NOTES

## Signal Chain Noise Analysis for RF-to-Digital Receivers

Design Note 439

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### Introduction

Designers of signal receiver systems often need to perform cascaded chain analysis of system performance from the antenna all the way to the ADC. Noise is a critical parameter in the chain analysis because it limits the overall sensitivity of the receiver. An application's noise requirement has a significant influence on the system topology, since the choice of topology strives to optimize the overall signal-to-noise ratio, dynamic range and several other parameters. One problem in noise calculations is translating between the various units used by the components in the chain: namely the RF, IF/baseband, and digital (ADC) sections of the circuit.

Figure 1 shows a simplified system diagram. There is an RF section, an IF/baseband section (represented by an amplifier) and an ADC. The RF section, which includes a mixer or demodulator, is commonly specified using noise figure (NF) in a decibel scale (dB). This may also be specified with a noise power spectral density which is similar to NF in concept (e.g.,  $-160\text{dBm}/\text{Hz}$ ) is

equal to an NF of approximately 14dB), so here we use NF. When working in a fixed-impedance ( $50\Omega$ ) environment, using NF simplifies the analysis of an RF signal chain. However, if the assumptions of constant impedance and proper source/load termination are not valid, then NF calculations become less straightforward.

IF/baseband components, such as amplifiers, are typically specified with noise spectral density, which is commonly measured in volts and amps per square-root Hertz ( $\text{nV}/\sqrt{\text{Hz}}$  and  $\text{pA}/\sqrt{\text{Hz}}$ ). The contribution of current noise ( $\text{pA}/\sqrt{\text{Hz}}$ ) is usually negligible in low impedance environments. ADC noise is primarily specified as a signal-to-noise ratio (SNR) in decibels. SNR is the ratio of the maximum input signal to the total integrated input noise of the ADC. In order to perform a full signal chain analysis, a designer needs to be able to translate between NF, noise density and SNR.

### NF to SNR: How Much ADC Resolution?

The first transition is from the RF section to the IF/baseband section. NF is a convenient unit, but requires constant system impedance. Since noise spectral density is independent of impedance, converting from NF to  $\text{nV}/\sqrt{\text{Hz}}$  makes sense, since in the transition from RF to baseband (node 1 in Figure 1), the chain is leaving the fixed  $50\Omega$  environment. At node 1, the noise voltage density due to the RF part of the chain can be represented as:

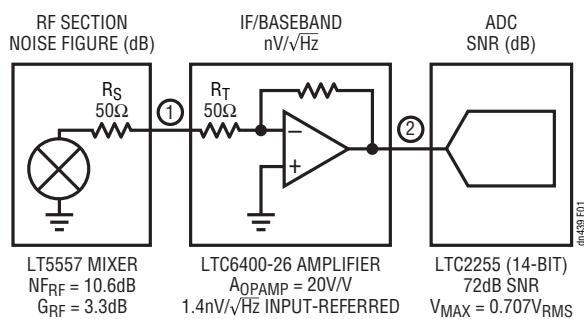
$$e_{N(RF)} = 10^{\left[\frac{(G_{RF} + NF_{RF})}{20}\right]} \cdot e_{N(50)} \cdot 0.5 \left(\frac{\text{nV}}{\sqrt{\text{Hz}}}\right)$$

where  $G_{RF}$  = cascaded gain of RF component(s) in dB

$NF_{RF}$  = cascaded NF of RF component(s) in dB

$e_{N(50)}$  = noise density of  $50\Omega$  ( $0.91\text{nV}_{\text{RMS}}/\sqrt{\text{Hz}}$  at  $27^\circ\text{C}$ )

$0.5$  = resistive divider from load termination, equal to 0.5 if  $R_T$  and  $R_S$  are  $50\Omega$ .



**Figure 1. Block Diagram of a Simplified Signal Chain with RF Components (Mixer, LNA, etc.), IF/Baseband Components (Represented by a Simple Amplifier) and an ADC. The Input Resistor of the Amplifier Serves as a Matched Termination for the  $50\Omega$  RF Section. A Suggested Product, and Its Specification for Each Section, Are Included**

With the LT5557 shown in Figure 1,  $e_{N(RF)}$  comes out to 2.25nV/ $\sqrt{\text{Hz}}$ . The input-referred voltage noise density of the IF/baseband section (including op amp resistors) can be computed using the op amp data sheet and summed with the contribution from the RF portion (using sum-of-squares addition since the specified values are RMS). Multiplying the result by the amplifier gain (V/V) gives the total noise density at node 2, ignoring the ADC's effective contribution:

$$e_{N2} = A_{\text{OPAMP}} \cdot \sqrt{e_{N(\text{OPAMP})}^2 + e_{N(\text{RF})}^2} \left( \frac{\text{nV}}{\sqrt{\text{Hz}}} \right)$$

Using the LTC6400-26 amplifier's specifications,  $e_{N2}$  comes out to 53nV/ $\sqrt{\text{Hz}}$ . The final step is to compute the overall SNR at the ADC. To do so, one must know the total integrated noise at node 2. Assuming the noise spectral density is constant with frequency, one can simply multiply  $e_{N2}$  by the square root of the total noise bandwidth. This bandwidth is limited by the amplifier circuit and any ADC antialias filtering. Assuming a total bandwidth of 50MHz, the integrated noise in our example is  $N2 = 375\mu\text{V}_{\text{RMS}}$ . The total theoretical SNR can be calculated as:

$$\text{SNR}_{\text{THEORETICAL}} = 20 \cdot \log_{10} \left( \frac{V_{\text{MAX}}}{N2} \right) (\text{dB})$$

where  $V_{\text{MAX}}$  = maximum sine wave input to the ADC in  $\text{V}_{\text{RMS}}$  ( $V_{\text{P-P}} \cdot 0.35$ )

$N2$  = total integrated noise at node 2, excluding the ADC, in  $\text{V}_{\text{RMS}}$

This theoretical SNR, which is 65.5dB in the example, represents the maximum resolution attainable with a perfect ADC. The actual ADC should have an SNR at least 5dB above this number to maintain the performance level down the chain. For example, a practical high performance 14-bit ADC, like Linear Technology's LTC2255 family (or LTC2285 family of dual ADCs), would have an SNR in the 72dB to 74dB range.

## SNR to NF

For radio designers, an important consideration in system design is total noise figure, which is affected by all components in the chain. Once the components are selected, one can determine the equivalent input noise figure and the overall sensitivity of the receiver. Assuming that the signal(s) of interest lie within one Nyquist bandwidth of the ADC (a Nyquist bandwidth is  $f_{\text{SAMPLE}}/2$ ), the equivalent noise of the ADC is:

$$e_{N(\text{ADC})} = 10^9 \cdot \frac{V_{\text{MAX}}}{10^{\left( \frac{\text{SNR}_{\text{ADC}}}{20} \right)}} \cdot \frac{1}{\sqrt{\frac{f_{\text{SAMPLE}}}{2}}} \left( \frac{\text{nV}}{\sqrt{\text{Hz}}} \right)$$

where  $\text{SNR}_{\text{ADC}}$  = data sheet SNR at the frequency of interest in dB

$f_{\text{SAMPLE}}$  = sample rate of the ADC in Hertz

In our example,  $e_{N(\text{ADC})}$  comes out to 22.5nV/ $\sqrt{\text{Hz}}$ , assuming a 125MHz sample rate. This voltage noise density,  $e_{N(\text{ADC})}$ , can then be RMS-summed with the amplifier output noise density,  $e_{N2}$ , and the result input-referred by dividing by the gain,  $A_{\text{OPAMP}}$ . To convert back to NF, rearrange the first equation in this article:

$$\begin{aligned} \text{NF}_{\text{TOTAL}} &= \\ &\left\{ 20 \log_{10} \left( \frac{\sqrt{e_{N(\text{ADC})}^2 + e_{N2}^2}}{A_{\text{OPAMP}} \cdot e_{N(50)} \cdot 0.5} \right) - G_{\text{RF}} \right\} (\text{dB}) \end{aligned}$$

This quantity,  $\text{NF}_{\text{TOTAL}}$ , gives the overall input noise figure with the contributions of the RF section, the amplifier and the ADC. In the example,  $\text{NF}_{\text{TOTAL}}$  is 12.7dB for the entire chain of three devices.

## Conclusion

When working with an entire system design from RF components to ADC, noise specifications do not always use the same units from component to component. This article addresses the translation between the various nomenclatures. Radio designers can use this information to design their system topology and select components for optimal sensitivity.

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