How the ADC noise figure impacts RF receiver designs

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Introduction

In an effort to build smaller digital receivers, the aerospace and defense industry is embracing modern direct radio-frequency (RF) sampling analog-to-digital converters (ADCs). These ADCs eliminate RF mixing stages and are closer to the antenna, simplifying digital receiver designs while also saving cost and printed circuit board (PCB) area.

One critical (and often misunderstood) parameter is the ADC noise figure, which sets the amount of RF gain to detect very small signals. This article explains how to calculate the noise figure of an RF-sampling ADC, and illustrate how the ADC noise figure affects RF signal-chain designs.

Why the noise figure matters in digital receiver designs

The digital receiver operates in one of two distinct scenarios as illustrated in **Figure 1**. In the blocking condition, an interferer or jammer is present and the receiver has to operate with reduced RF gain in order not to saturate the ADC. In this setup, the ADC is driven close to full scale by the interferer; thus, the large-signal signal-to-noise ratio (SNR) of the ADC determines how weak a signal can be detected. There are additional degrading mechanisms such as phase noise and spurious free dynamic range.

In the second scenario, there is no interferer present. Detecting the weakest signal possible is solely dependent on the inherent noise floor of the receiver, a condition typically measured as receiver sensitivity. The noise figure measures the SNR degradation caused by components in the receiver signal chain.

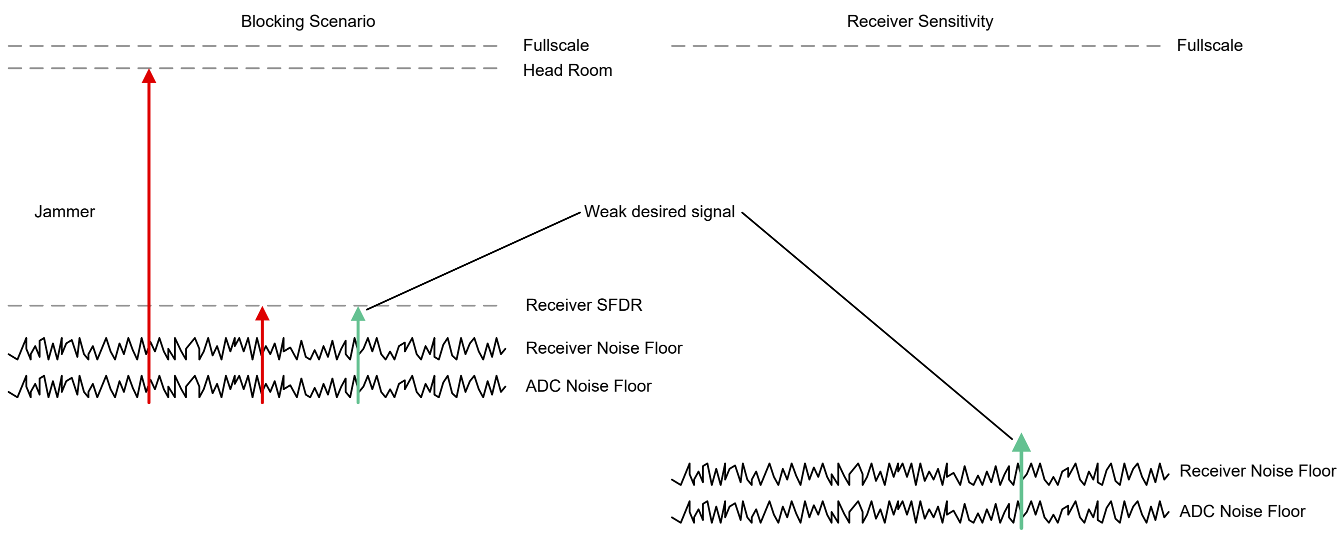

Figure 1. *Comparison between blocking or jamming and receiver sensitivity scenarios.*

The noise figure of the ADC is typically the weakest link of the receiver (approximately 25 to 30 dB), while low-noise amplifiers (LNAs) have noise figures as low as <1 dB. It is possible, however, to improve the ADC noise figure by adding gain to the analog RF front end (close to the antenna) using LNAs. The difference between a 1-dB receiver system noise figure and a 2-dB receiver system noise figure translates to approximately 20%. This difference means that a receiver with a 1-dB noise figure can detect signals with approximately 20% weaker amplitude. In a software-defined radio (SDR), that translates to radios with reduced output power – saving battery life – while in radar, that makes it possible to cover a longer distance.

Modern receiver designs in SDRs or digital radars use direct RF-sampling ADCs in order to reduce size, weight and power. This architecture simplifies receiver designs by eliminating the RF downconversion mixing stage. The better the ADC noise figure, the less gain required, which results in additional savings. Furthermore, using less additional RF gain means that when a jammer is present, there is less gain to reduce, with a higher dynamic range maintained in the receiver.

Calculating a system's noise figure

You can use the Friis equation to calculate a receiver system's noise figure. Assuming a simplified, ideal receiver with two amplifiers and one ADC, as shown in **Figure 2**, **Equation 1** calculates the cascaded system noise factor as:

$$F_{System} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \cdot G_2} + \ldots + \frac{F_n - 1}{G_1 \cdot G_2 \ldots \cdot G_{n-1}} \quad (1)$$

where F_x are the noise factors and G_x are the power gains.

The system noise figure in decibels is:

$$NF_{System} = 10 \log(F_{System}) \quad (2)$$

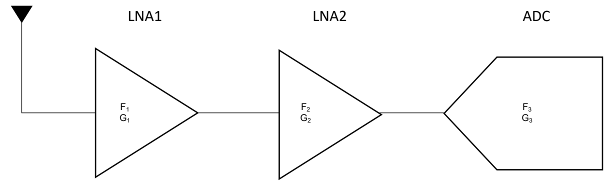

***Figure 2.** Typical receive signal chain.*

There are two important things to highlight: the system noise figure is primarily dominated by the noise figure F_1 of the first element, as long as gain G_1 and G_2 are large enough to where the ADC noise figure F_3 is negligible.

Comparing two different ADCs with 20-dB vs. 25-dB noise figures in a system with two cascaded LNAs shows a drastic difference in system noise figures (see **Table 1**).

	LNA1	LNA2	ADC1	ADC2
Noise figure	1 dB	3 dB	20 dB	25 dB
Gain	12 dB	15 dB	0 dB	0 dB
Resulting system noise figure			1.8 dB	2.9 dB

***Table 1.** System noise figure with two LNA stages.*

Getting the system listed in the ADC2 column (with a 5-dB worse noise figure) to a system noise figure below 2 dB would require an additional 10 dB of gain using a third LNA (noise figure = 3 dB), as shown in **Table 2**.

Table 2 highlights the impact of the ADC noise figure on the overall system noise figure. Adding a third LNA increases cost, board area (matching components, routing and power supply) and system power consumption, and further reduces the full-scale headroom.

	LNA1	LNA2	LNA3	ADC2
Noise figure	1 dB	3 dB	3 dB	25 dB
Gain	12 dB	15 dB	10 dB	0 dB
Resulting system noise figure				1.4 dB

***Table 2.** System noise figure using ADC2 with three LNA stages.*

Assuming a target receiver sensitivity of –172 dBm, or very weak signals just 2 dB above the absolute noise floor (–174 dBm + 2 dB = –172 dBm), this receiver requires an noise figure better than 2 dB. Let's use the above example with ADC1 (with a 20-dB noise figure, as listed in Table 1) and a cascaded system noise figure of 1.8 dB.

As shown in Figure 3 and Table 3, LNA1 with a gain of 12 dB raises both the input signal and noise by 12 dB while degrading the noise figure by 1 dB (noise figure_{LNA1} = 1 dB). LNA2 raises both signal and noise by 15 dB. Even though LNA2 has a higher inherent noise Figure 3 dB, its impact is reduced to just 0.2 dB because of the 12-dB gain of LNA1.

Finally, the noise contribution of ADC1 (noise figure = 20 dB) reduces to just 0.6 dB, as it gets reduced by the 27-dB gain of both LNAs. Therefore, you end up with a system noise figure of 1.8 dB, which leaves approximately 0.2 dB of headroom to detect weak input signals.

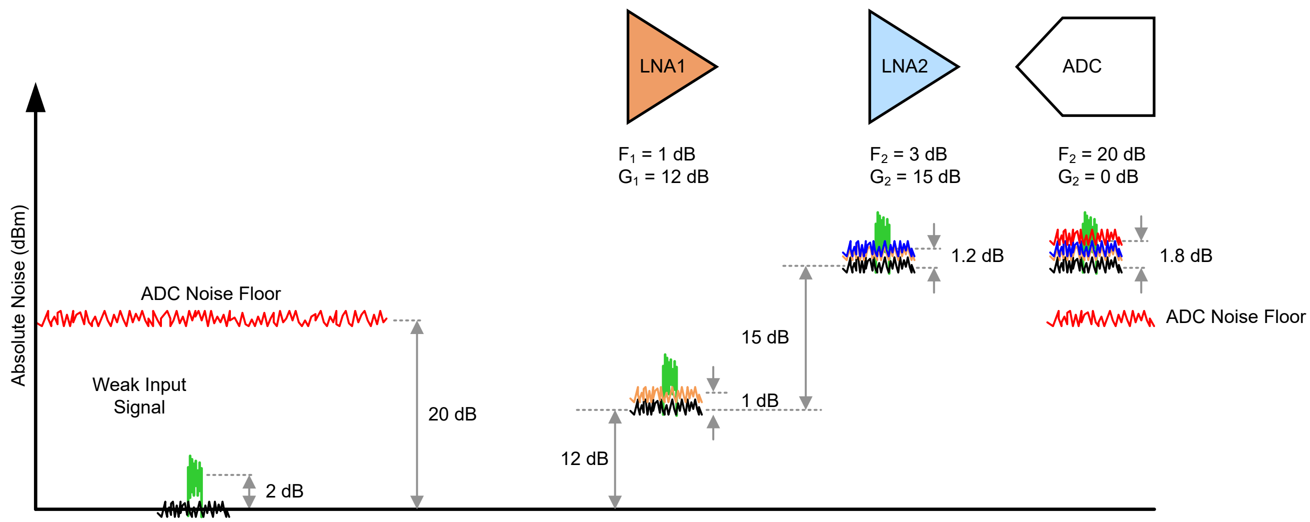

Figure 3. *Graphical illustration of the individual noise figure contributions in a receive signal chain.*

	LNA1	LNA2	ADC
Noise figure (dB)	1	3	20
Gain (dB)	12	15	0
Noise power (linear) 10^(noise figure/10)	1.26 $10^{1/10}$	2 $10^{3/10}$	100 $10^{100/10}$
Power gain (linear) 10^(gain/10)	15.85 $10^{12/10}$	31.62 $10^{15/10}$	1 $10^{0/10}$
Noise figure of LNA1 only (dB)	1	–	–
Noise figure of LNA1 + LNA2 only (dB)	1.2 10log[1.26+(2-1)/15.85]		–
Noise figure of LNA1 + LNA2 + ADC (dB)	1.8 10log[1.26 + (2-1)/15.85 + (100-1)/15.85/31.62]		
Additional impact on system noise figure (dB)	1	0.2	0.6

Table 3. *Calculations for individual noise figure contributions.*

High-speed data converters rarely list noise figure in the device-specific data sheet. The noise figure for an ADC can be calculated using Equation 3 using the common data-sheet parameters (see Table 4) for the ADC32RF54 RF-sampling ADC.

Parameter	Description	ADC32RF54 (1 times AVG)	ADC32RF54 (2 times AVG)
V	Input full-scale voltage peak to peak (V_{pp})	1.1	1.35
R_{IN}	Input termination impedance (Ω)	100 Ω	
FS	ADC sampling rate	2.6 GSPS	
SNR	ADC SNR for small-input signals (dBFS), typically –20 dBFS	64.4	67.1

Table 4. *Data sheet parameters of the ADC32RF54.*

$$\text{ADC Noise figure (dB)} = P_{SIG,dBm} + 174\ \text{dBm} - \text{SNR (dBFS)} - \text{bandwidth (Hz)}$$

$$NF_{ADC}\,(dB) = 10\log\left(\frac{\left(\frac{V}{2\times\sqrt{2}}\right)^2}{R_{IN}} \times 1000\right) + 174 - SNR \quad (3)$$

$$-\ 10\log\left(\frac{FS}{2}\right)$$

For the **ADC32RF54**, the noise figure calculates to:

Noise figure (1x AVG) = 20.3 dB

$10\log[(1.1/2/\text{sqrt}(2))^2/100 \times 1000] + 174 - 64.4 - 10\log[2.6e9/2]$

Noise figure (2x AVG) = 19.3 dB

$10\log[(1.35/2/\text{sqrt}(2))^2/100 \times 1000] + 174 - 67.1 - 10\log[2.6e9/2]$

Conclusion

The receiver noise figure is an important system design parameter because it determines the weakest detectable signal. In addition to a very low inherent noise figure, the **ADC32RF54** also provides a high SNR, which allows the system to maintain its noise figure even with a larger-input power signal. An ADC with same noise figure but a lower SNR would require a reduction in the input gain to prevent saturation, in which case the ADC noise figure starts adding more to the overall noise.

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