Application Note

How to Reduce Noise in Audio Data Converters

Arash Loloee

ABSTRACT

Despite advances in DAC technology, noise remains a significant factor affecting audio quality. Noise introduced within a DAC can degrade signal fidelity, reduce dynamic range, and impact the listener's experience.

Noise is an unwanted signal present along with the main and intended signal. Noise by nature is random and is unwanted, especially in audio systems. There are many different sources of noise that are either from within the audio IC (internal) or the board, external components and layout (external) in which the audio IC is residing. While there are many different sources of noise, there are a few methods to reduce or contain noise. In this application note, we will address different sources for noise and how to minimize their effect on the desired audio signal.

This topic will be divided into two parts. First the noise within the IC and methods to reduce or eliminate it by design and selection of architecture are discussed and then the noise that is external to the main IC and within the system will be discussed.

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1 Introduction

Any data converter is made of analog and digital modules that together achieve the task of data conversion, whether it is an analog signal to digital conversion (ADC) or digital signal to analog conversion (DAC). These modules consist of many sub blocks. For example, a digital module might include I2C/SPI, clock generators, digital filters, audio serial interface, digital gain block, etc. The analog module might include the voltage refence blocks such as bandgap, current generator, gain amplifier, mixer to name a few in the analog section.

This application discusses the noise in audio converters, and the concepts are valid not only to DACs but also applicable to ADCs and CODECs.

2 Detailed Description

2.1 Internal Noise (Within the IC)

2.1.1 Noise Shaping and Filtering Out the Noise

In digital conversion, continuous signal amplitudes are approximated by discrete digital values. When the DAC reconstructs the signal, the finite resolution of the digital data results in small amplitude errors.

The mapping of a digital code to a range of analog signals creates an error that is referred to as quantization noise. The transfer function of a DAC is a series of discrete points as shown in Figure 1. In this figure, the mapping of digital code to corresponding analog output for a 3bit DAC is shown. For a DAC, 1 LSB corresponds to the height of a step between successive analog outputs.

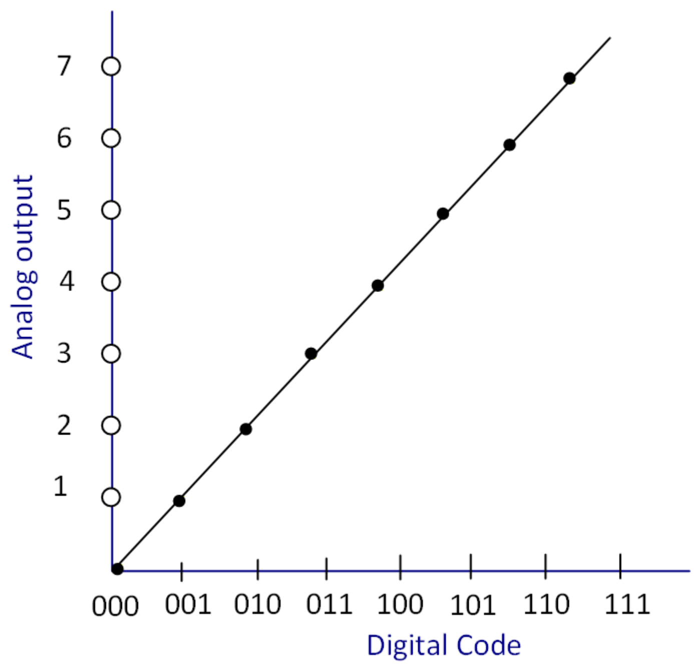

Figure 2-1. Typical Transfer Function of a 3 Bit DAC

An N-bit converter has 2^N levels of quantization. Therefore, the width of these quantization levels are FS/(2^N-1). For an ADC with a quantization width of Δ, the quantization noise has equal probability to fall anywhere between –Δ/2 to +Δ/2, and a probability density function that is uniform over the range of quantization error. The quantization noise power can be calculated by integrating the error over this range as given in Equation 1 :

$$\varepsilon_{rms}^2 = \frac{1}{\Delta}\int_{-\Delta/2}^{\Delta/2} \varepsilon^2\, d\varepsilon = \frac{1}{\Delta}\frac{\varepsilon^3}{3}\Bigg|_{-\frac{\Delta}{2}}^{+\frac{\Delta}{2}} = \frac{\Delta^2}{12} \tag{1}$$

In general, one can sample the signals with a frequency that is much greater than Nyquist frequency. The ratio of sampling frequency at higher sampling frequency (f_{OS}) to Nyquist frequency (2fO) is called an oversampling ratio (OSR), where f_O is the frequency of the input signal. So OSR can be written as shown in Equation 2:

$$OSR = \frac{f_{os}}{2f_o} \tag{2}$$

Under oversampled conditions, the noise power that falls within the signal bandwidth (0 to fO) is given by Equation 3

$$n^2 = \int_0^{f_o} \varepsilon^2(f)df = \varepsilon_{rms}^2\left(\frac{2f_o}{f_{os}}\right) = \frac{\varepsilon_{rms}^2}{OSR} \tag{3}$$

As is shown in the above equation, oversampling reduces the in-band rms noise by the square root of the oversampling ratio. In fact, by oversampling, the noise spectrum is distributed over a wider range of frequency. What about shaping the noise and pushing most of the noise spectrum to higher frequencies, such that the in-band noise is reduced even more? This concept is called “noise shaping (Ref.3). After noise shaping, all that needs to be done is to filter out the noise at high frequencies. Filtering can be done in the digital or analog domain. When the bit stream comes out of the modulator, a digital filter is appropriate. Since we oversampled by a factor of K, noise is pushed out to higher frequencies. By filtering at fs/2, the majority of the noise will be out-of-band. A low-pass RC filter with appropriate cut-off frequency is usually used at the output of the DACs.

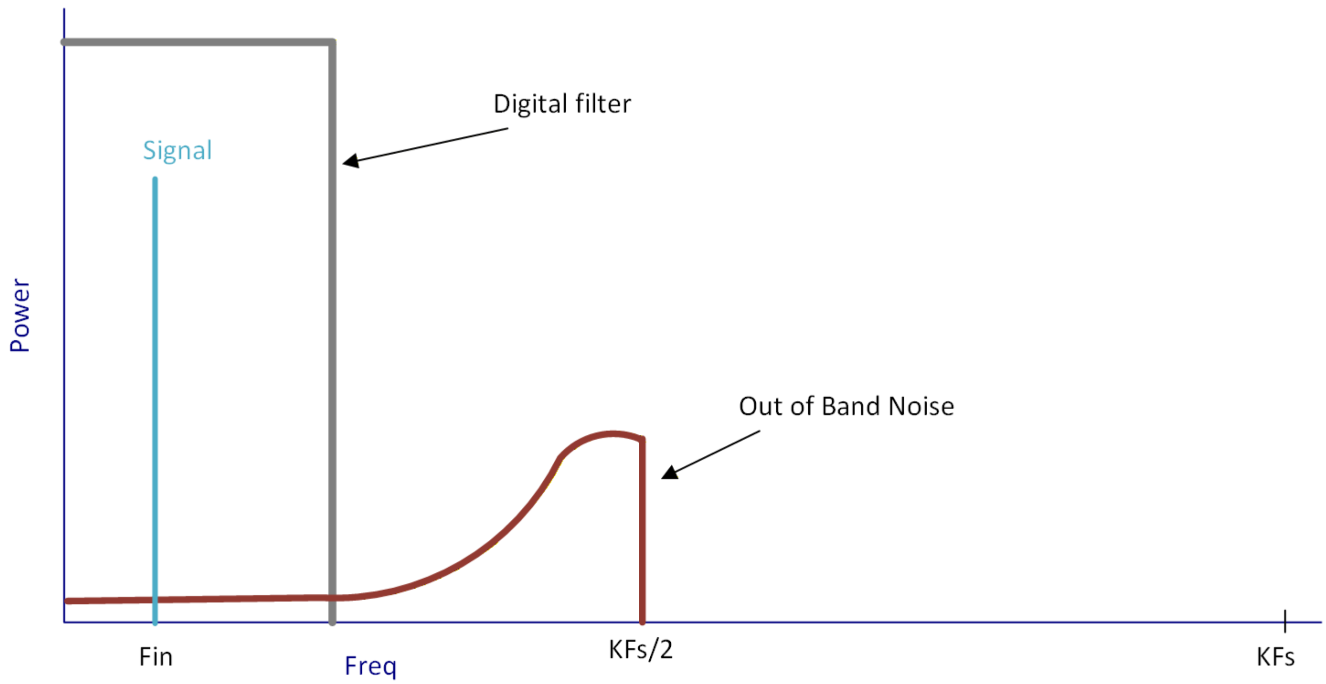

Figure 2-2. The Noise Spectrum Distributed Over Kfs With Noise Shaping

2.1.2 Avoiding Noise Coupling between Internal Digital and Analog Modules

Similar to the PCB design, in which the placement of digital and analog sections is planned carefully, the internal design of the DAC follows a similar approach. The analog and digital domains are separated, and each requires dedicated power supplies.

Clocks are the most dominant source of noise injection to the ground lines and thus the analog and digital domains must be isolated with their own ground lines. In many designs submodules exist within the main module and have separate supplies to help with containing the noise within a submodule. In all of TI's audio devices, not only the digital, analog, and IO buffer supplies are separated, but also in many cases multiple ground pins or independent supplies are provided for each submodule or channel. Care must be taken in the layout phase as well by isolating or shielding to complete the noise containment attempts.

While the end users have no control over the design and layout of a given IC, the selection of the part with suitable architecture and features can improve the performance of the system as a whole.

2.2 External Noise

Once the selection of the DAC is done, the next step is the design a board that can bring out the performance of the DAC without any degradation coming from the board and external components. Clocks and power supplies are two of the top contributors of noise injected into a system. We will briefly go over the items that can contribute to higher noise in a system and how to address them for better noise performance.

2.2.1 Clock Jitter

The clock jitter will introduce sampling error which results in degradation of SNR. Jitter can result in distortion and increased noise floor. The increased noise floor has direct effect on the degradation of SNR. Equation 4 quantifies the effect of jitter error on SNR as

$$SNR = 20\log\left(\frac{Vp/\sqrt{2}}{2\pi f_{in}Vp.t_j/\sqrt{2}}\right) = -20\log\left(2\pi f_{in}t_j\right) \tag{4}$$

Where t_j, f_{in} and V_p are the jitter, input frequency and amplitude of the signal respectively. You can read more about the details of jitter and SNR relationship and the derivation of the above equation in the provided Ref.4.

2.2.2 Power Supplies

Like any other data converter, DAC performance depends heavily on clean power supplies. Voltage fluctuations, switching noise from regulators, and electromagnetic interference can be coupled into sensitive analog circuitry.

A clean power supply source is highly recommended as it provides stable, noise-free, and well-regulated electrical power to the board and the DAC among other ICs on the board. A low noise power supply provides minimal AC ripple or high-frequency noise superimposed on the DC output. It also provides low EMI and fast transient response when sudden changes in load current occur.

One important practice to ensure having a clean supply source is to add decoupling/bypass capacitors to the supply pins of the DAC. It must be noted that the decoupling caps are dedicated capacitors for each individual supply pin. Even if the voltage levels or the source of the supply voltages for several supply pins is the same, still dedicated decoupling capacitors must be added for each pin (Figure 2-3). Usually, multiple bypass capacitors in different decade ranges are added to each supply pin to suppress noise across a broad frequency spectrum. High-frequency noise requires small caps (such as 100pF ceramic), while lower-frequency noise needs larger values (1µF). TI recommends using low-ESR (Equivalent Series Resistance) capacitors (e.g., ceramic) to minimize ripple and noise. These decoupling caps must be placed as close as possible to the corresponding pins at the chip.

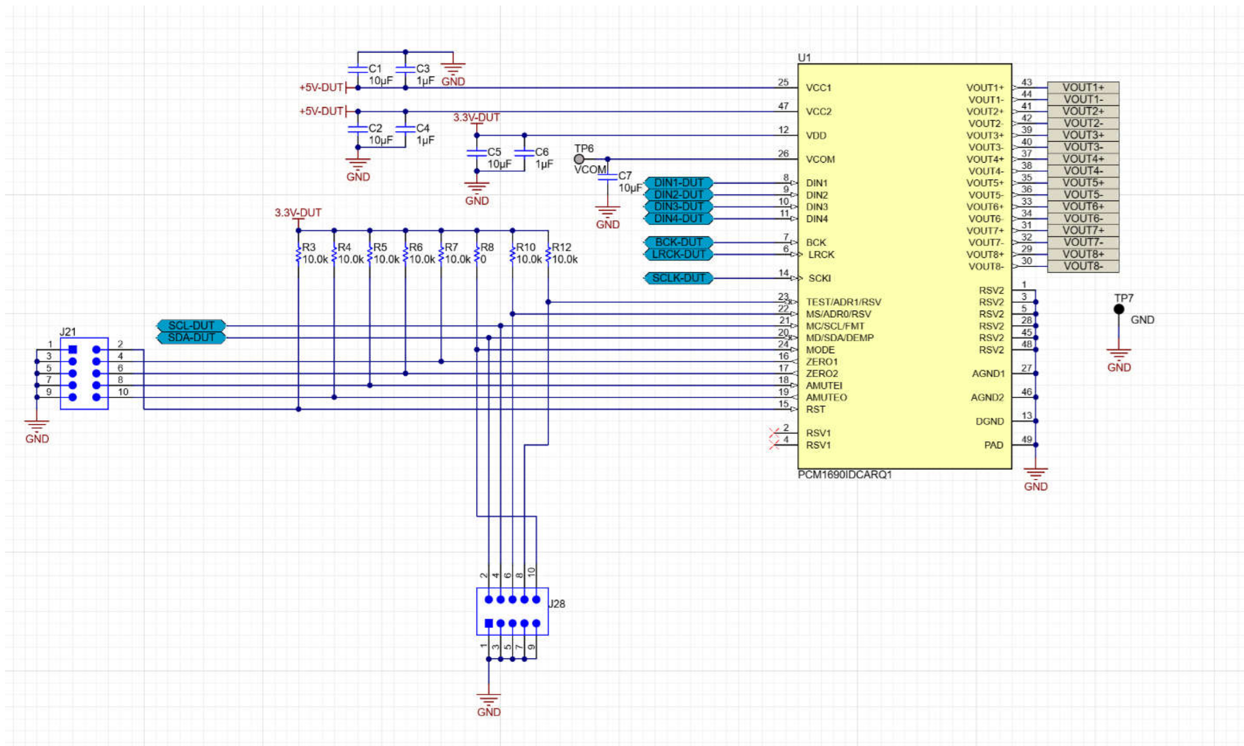

Figure 2-3. Bypass Capacitors Connected to Each Supply Pin (PCM1680)

Another common practice for having a cleaner supply source is to add ferrite beads or LC filters to filter high-frequency noise from power supply lines. These ferrite beads must be placed at the input of the power entry point.

2.3 Noise from PCB Design and Routing

Another important source of noise injected into a DAC is due to routing of various signals on the board. Appropriate printed-circuit-board layout guidance along with grounding techniques should be followed to eliminate ground loops, parasitic effects, and noise.

- *Use Separate analog and digital supplies if possible*. Separate analog and digital supplies are recommended for most boards that have digital and analog supply pins. In most cases, there are different ICs that are using the same voltage levels; thus, the same supply is shared among them. These ICs can be switching at different frequencies, and the switching noise could be injected into all ICs that share the same supply line. As was mentioned in the previous section, to reduce or remove the injected noise to the supply line, decoupling capacitors should be added to each supply pin and these capacitors must be placed as close as possible to the physical pin.
- *Use a solid, unbroken, low-inductance ground plane across the board*. This is the single most effective measure against noise. The most common issue in the layout of a board is ground loops where return current from one IC flows through paths shared with other analog or digital ICs. A low-frequency hum or buzz usually is the result of ground loops.
- The classic approach to deal with ground loops is to have separate solid planes for analog and digital ground planes. These ground planes should be connected to each other at a single point to form a combined ground and prevent noisy digital return currents from flowing through the analog ground throughout the circuit.
- Component placement impacts signal quality, thermal management, and electromagnetic interference (EMI) to name a few parameters that can be affected. Poor placement of components can lead to issues like crosstalk, signal delays, and increased noise.
- Orientation of ICs and their placement often can make a difference in routing. It is better to place the ICs in the same direction so that routing traces can flow naturally without unnecessary turns.
- Follow the best practices for layout design. These practices usually are simple and common sense but easily can be overseen or neglected:
- Keep lead lengths as short as possible, especially on sensitive analog input and output signals. Long traces can act as antennas, picking up or radiating electromagnetic interference (EMI). It is recommended that three times the width of a sensitive trace should be used as a keep-out or clear zone around the trace.
- Maintain a restricted area around sensitive traces to minimize capacitive coupling.
- Separate input traces from output traces to prevent feedback and coupling of output noise back to the input and vice versa.
- Avoid routing high-speed or switching signals near analog or sensitive signal traces.
- When applicable, route differential signals parallel to each other to maintain a constant spacing and length for both signals to ensure common-mode noise cancellation.
- Use guard rings around sensitive lines to shield them from the noise coupling to them. The guard rings should be tied to a ground plane to bleed off leakage currents.

3 Summary

Noise remains one of the most important factors influencing audio DAC performance. In this application note, various sources of noise such as quantization error, thermal noise, clock jitter, power supply fluctuations, and digital switching interference that contribute to degradation of the reconstructed analog signal were discussed. Through advanced design techniques including oversampling, noise shaping, low-jitter clocking, and careful circuit layout, modern DACs achieve remarkably low noise levels and exceptional audio fidelity. The right selection of the DAC along with adhering to the best practices for designing the board would reduce the effect of noise that degrades the audio quality in an audio system.

4 References

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