Audio ADCs Hit the High Notes

Jon Titus, Senior Technical Editor

Everything from filter performance and software to clock signals and PCB layouts affects audio-ADC performance.

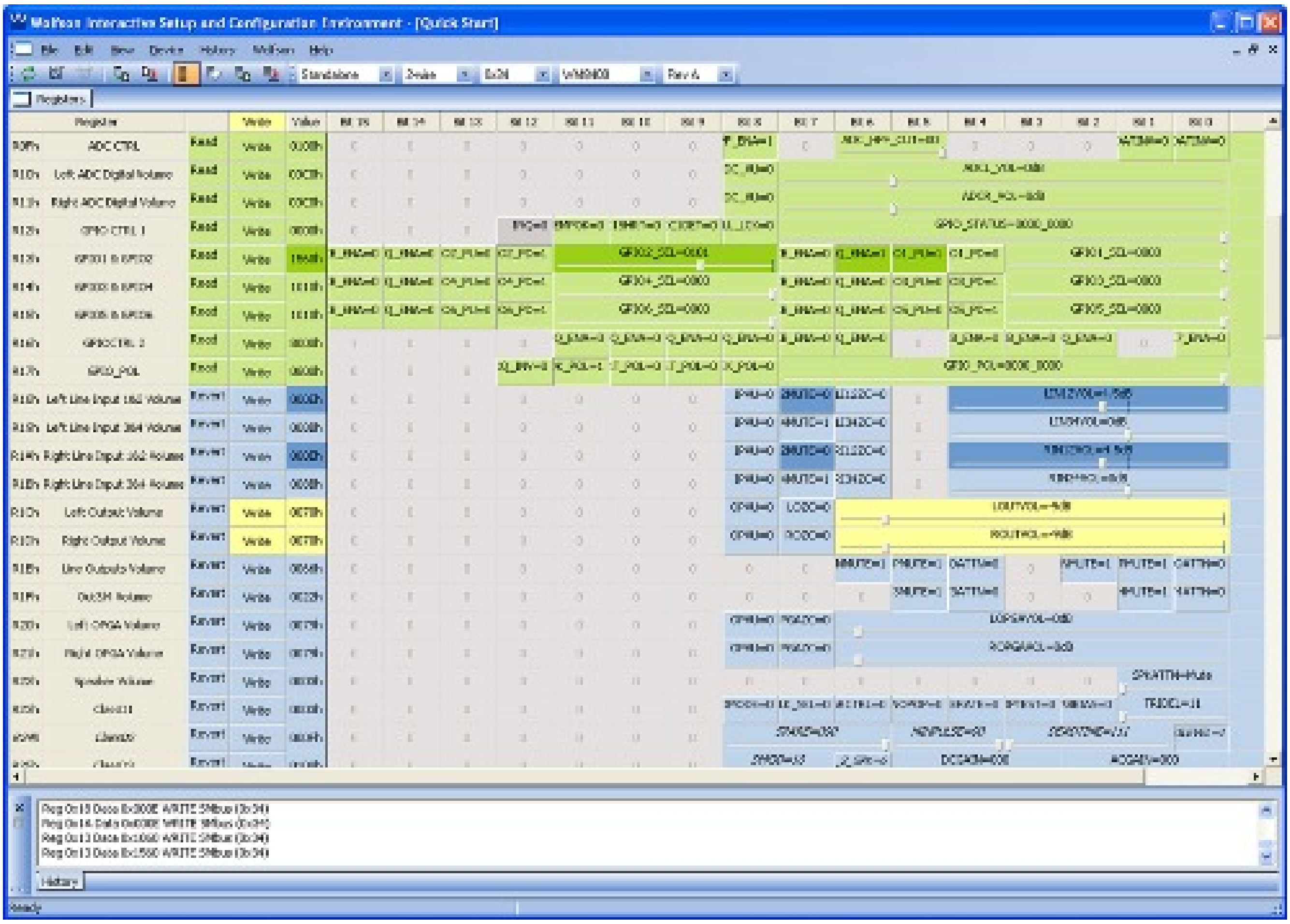
Although engineers have used analog-to-digital converters (ADCs) for some time, newer ADCs aimed at audio applications can put design skills to the test. The audio signal chain in current products and new designs can involve more stringent design requirements than engineers have faced in the industrial world.

"To start, we need to know about the application and its requirements," said James Scanlan, Americas applications manager at Wolfson Microelectronics, a supplier of high-end ADCs, DACs, and codecs. "Is it a voice product? Does it need high fidelity? Will it operate in a noisy environment? Must it conserve power? What are the signal-to-noise ratio [SNR] and the total harmonic distortion [THD] requirements? Answers to those and similar questions help us guide designers to specific ADCs and CODECs."

"Say you produce high-end automotive stereo systems," said Scanlan. "You have a head unit in the car's dashboard that puts out four channels of audio in analog form. The car-trunk amplifier's ADCs sample the audio signals, process them, and drive speakers. In that case, you need ADCs with a high SNR, but ADC power consumption become less important."

According to Bob Adams, a Fellow and manager of audio development at Analog Devices, ADCs designed for high-end audio applications now almost exclusively use the sigma-delta conversion technique. "And many engineers no longer use discrete ADCs, but design with audio codecs instead. You can get from one to eight ADCs and two to eight DACs in one codec package. The dynamic range of these codecs can be as high as 100 dB, which makes them a suitable choice for many consumer applications. Many of these devices also offer low power consumption for portable devices. If designs require higher performance and can tolerate somewhat higher power consumption, there are devices with dynamic-range specs that approach 120 dB, which make them suitable for the professional and automotive audio markets."

When Do 24 Bits Equal 16?
"Many engineers who have used an ADC for industrial measurements can get a bit confused when we talk about audio sigma-delta ADCs with 24-bit resolution," said Dafydd Roche, home and audio pro product marketing manager at Texas Instruments. "Often people think a 24-bit ADC means they will get 24 bits of useful information. But in some cases a 24-bit converter can perform worse than a regular 16-bit converter. A 24-bit ADC that has a 96-dB dynamic range produces about 16 bits of real data. Even though you get 24 bits in the ADC's serial output stream, you have only 15 or 16 bits of real data and the rest of the bits are noise or zeros."



The WISCE software lets users easily view and change settings for Wolfson

ADCs and similar ICs. This software uses slider controls to view and set volume and I/O port values in specific bit positions. Courtesy of Wolfson Microelectronics.

"The noise inherent in CMOS devices limits ADC performance to less than 24 bits, or less than 144 dB," noted Robert Martin, a system engineer for audio converter products at TI. "I don’t believe any ADC today gets close to 144 dB. Engineers want to squeeze every decibel of performance out of an ADC, but they might inadvertently compromise their ADC's performance by including pre-amps, filters, or other analog stages in their front-end circuits. If they specify a high performance ADC and then use low-performance op-amps in those front-end circuits, that asks for trouble. The ADC input circuitry must be carefully considered in order to achieve the best converter performance. Using a noisy op-amp to amplify a small audio signal might cause the amplified noise of the op-amp to degrade the ADC's performance. So it’s like driving a Ferrari with the parking brake on: It’s a great car but you can't go at top speed."

Not every application demands a high dynamic range. "We see a large market for low-cost speech devices in products such as intercoms, elevators, toys, and speaker phones," said Steven Marsh, strategic marketing manager with Microchip’s Digital Signal Controller Division. "The audio spectrum for those devices ranges from zero to 8 kHz, as opposed to standard telephone-quality audio between zero and 3.3 kHz. Because cost is a key design influence, a 12-to-14-bit ADC — often within a controller chip — will suffice."

"Engineers frequently think they must use a 16-bit ADC in audio circuits," noted Sunil Fernandes, an applications engineer in Microchip's Digital Signal Controller Division. "But as they experiment with a 12-bit ADC they discover that’s not entirely true. They get good audio quality with only 12 bits. In a toy or intercom system, the characteristics of the speaker and microphone, rather than ADC resolution, often determine audio quality. So, a 12-bit ADC gives you a lot of 'head room' in these consumer-type products."

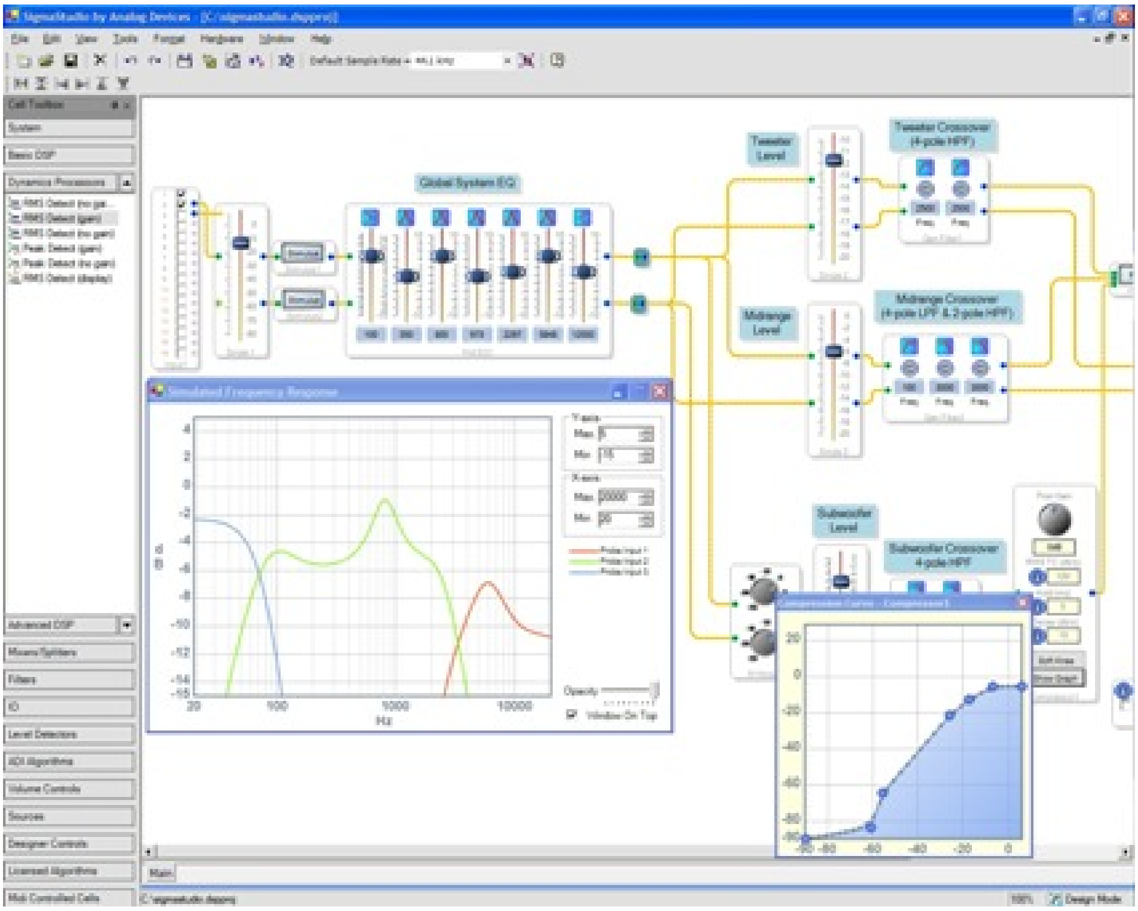
"People can take the MPLab Starter Kit for dsPIC DSCs and demonstrate how well a 12-bit ADC digitizes an audio signal," said Fernandes. "They can press a button, speak into a microphone, record 12-bit speech, and then play it back. The kit produces a PWM Class-D audio output they can listen to."

Oversampling Boosts Resolution

But suppose engineers decide they still need more resolution. "They can oversample an audio signal at 128 ksamples/sec to improve resolution of a 12-bit ADC by 1.5 to 2 bits," explained Fernandes. "So your ADC can have an effective resolution of 13.5 or 14 bits. That’s just one of the things designers can do within a dsPIC chip. Microchip has a variety of post-processing software libraries for functions such as equalization, filtering, spectral analysis, automatic gain control, noise-and-echo cancellation, and speech recognition."

In contrast to the sigma-delta ADCs used for many high-end audio applications, the dsPIC chips rely on a successive-approximation-register (SAR) ADC. Software can trigger SAR ADC conversions whereas a sigma-delta converter runs continuously. Although an SAR ADC usually requires a sample-and-hold circuit on its input, the Microchip dsPIC devices do not. The S/H comes built in.

A dsPIC-based circuit might need an anti-alias filter, though, depending on the application and sample rate. "Anti aliasing gets into the realm of digital filtering as well," said Marsh of Microchip. "Often engineers can replace a sophisticated analog filter with a simpler anti-aliasing filter and use digital-filter software. That approach significantly cuts the component count while it improves filter performance. A dsPIC-based circuit, for example, could combine the digital filter code with other wave-shaping software for an added benefit."



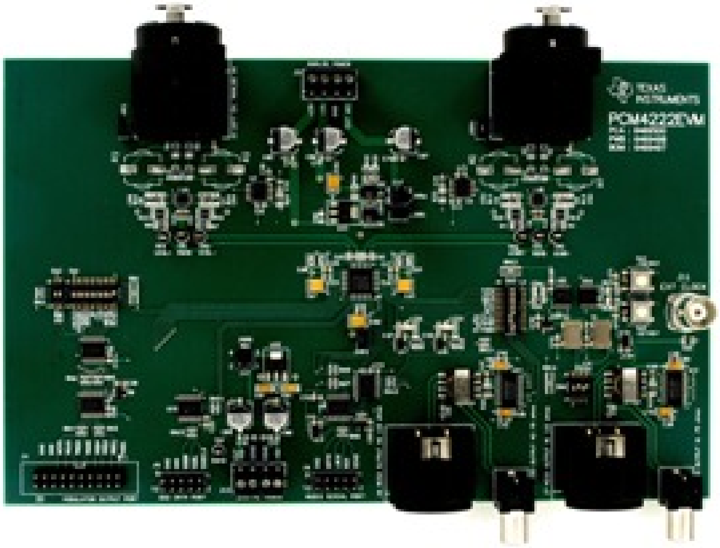
The SigmaStudio tool lets engineers with no DSP coding experience easily take advantage of the SigmaDSP engine within a codec such as the Analog Devices ADAU1761. Users can connect audio-processing blocks that an underlying compiler turns into DSP-ready codes. Courtesy of Analog Devices.

Look Beyond Resolution
Although ADC resolution first comes to mind when engineers look at ADCs, other performance characteristics deserve attention, too.

"Sigma-delta ADCs include a digital decimation filter that typically offers a linear-phase response through the audio pass band," explained TI's Martin. "Human ears will quickly detect out-of-phase audio signals. ADCs used with sensors in industrial applications usually don't require this type of phase linearity. So at first, engineers with industrial backgrounds might not appreciate the need for phase linearity in audio circuits."

Phase relationships become important at the signal-input side of ADCs, too. "We talk on our mobile phones in noisy environments," said Wolfson's Scanlan. "Typically a phone uses one microphone, but multiple microphones give engineers the opportunity to apply audio beam-steering techniques that help attenuate noise. But beam steering demands in-phase sound signals from those microphones. In this type of design you might have a discrete ADC next to each microphone to send digital data to a processor. By placing an ADC at each microphone, you no longer must run sensitive analog signals through digital and RF circuits that could add noise."

All ADC circuits must put up with some noise, and oversampling and noise shaping help decrease quantization noise. That type of noise arises normally in an ADC due to the quantization of a continuous signal into discrete samples. "Oversampling distributes quantization noise over a wider bandwidth — between DC and half the sampling frequency, while noise shaping moves a large chunk of the noise out of the Nyquist band," said TI's Martin.



Reduce Audio Noise

Acoustic noise also affects the acquisition of useful audio information. "But dealing with audio noise often involves more art than anything else," said Marsh. "Engineers have many ways to attenuate noise, but the methods they choose depend on the types of noise present and what the engineers need to achieve."

"You might think of noise as a high-frequency signal you can simply filter out," continued Marsh. "Noise suppression involves more than that. Suppose you must suppress noise from a factory area superimposed on someone's speech. You must first detect the speech and next determine when the speech isn't present. Then you sample the factory noise alone and use its characteristics to filter the acoustic noise out of the speech signal. That technique goes beyond a simple filter task." Microchip has noise suppression libraries that work with data from the 12-bit SAR ADCs in its dsPIC devices. These libraries now work with traditional telephone-quality signals, but the company expects to soon offer software that also operates on wide-band speech signals.

Beware of Spurious-Noise Incursions

Those engineers who plan to use sigma-delta ADCs should know about another type of "noise" that affects ADC performance. The design of the modulator circuit in sigma-delta ADCs can cause idle "tones" to appear in the pass band when the ADC has a low-level or no-audio signal at its input. This effect appeared more pronounced in older 1-bit modulation designs and usually is not an issue in proper multi-bit modulator designs. "In older designs, you could hear these spurious tones during a quiet period in the audio input," noted TI's Martin. "Newer sigma-delta IC designs handle idle tones by adding dithering or by adding a small offset. Typically DC offsets at an ADC's input cause the idle tones to appear."

"Electrical noise present on power-supply lines or at an ADC's reference-voltage can play havoc with high-resolution ADCs," said Adams of Analog Devices. "When you work with converters that have a 120-to-124-dB dynamic range, you must take pains to remove electrical noise from circuit power lines and from the ADC's Vref signal. Always treat the ADC Vref pin as sacred. Do not contaminate this pin with anything because it will just contaminate the data from your ADC." Engineers always must bring good analog circuit-design practices to bear on audio ADC circuits and PCB layouts.

Clock Circuits Keep Music in Time
To borrow (loosely) from Mark Twain, power and references are good, but it's the clock circuits that do the work. Many audio ADCs use the Inter-IC Sound bus (I-squared-S or I2S) to transfer digitized information to a processor or other device. Philips Semiconductors developed the standard specifically for audio ICs. The bus has at least three signal lines — clock, data, and word select. The word clock runs at the sample frequency of the ADC.

"The word clock is a bit like the heartbeat of the system," explained TI's Roche. "So even if you have eight stereo ADCs in a system, you can synchronize them with one word-clock signal that goes to each ADC. The majority of converters have a pin or a register setting that lets them behave as a master or a slave. In my experiences typically it’s best to have an ADC serve as a master."

"You can use an ADC in master mode or have a DSP or an FPGA that sends a clock over to an ADC operated in slave mode," said Martin of TI. "In either case you should derive all the ADC timing from a master clock in the system. That means all the ADC clock signals will be properly synchronized because they all derive from a single clock source."

"Like other manufacturers, we have ADCs that run on a clock available within the system, or a codec might include a PLL or a frequency-lock loop (FLL) to produce a 'solid' clock signal," said Wolfson's Scanlan. "An FLL is more efficient and it has a wider frequency range than a PLL. If you have a clock on a board but it doesn't provide the exact frequency you need, the FLL can help you get the frequency you need. Not all codecs or ADCs include a PLL or FLL, so engineers must determine if they need one of these functions or if they can use a clock signal already present in their design. That's an important consideration that helps engineers narrow their choices of ADCs and codecs."

Hunt Down Jitter Bugs
"Clock jitter causes less worry in multi-bit sigma-delta converters than it did with 1-bit ADCs," explained Adams of Analog Devices. "You want to aim for jitter in the range of hundreds of picoseconds. The PLLs built into codec chips also have helped reduce jitter."

You can relate clock jitter to PCB design, too. "Look at how you distribute clock signals," said TI's Roche. "If you lay them out improperly and without attention to timing, you could end up with clock jitter which will cause some distortion. As the sampling time moves back and forth slightly due to jitter, you find more distortion introduced at high audio frequencies. If designers see a lot more distortion at high frequencies compared to the datasheet specs, and that distortion isn’t present on the analog input to the ADC, it might indicate they have a clock-generation or -distribution issue that causes jitter. In examples of poor PCB layout, digital clock lines can couple with audio level PCB traces, potentially introducing additional high frequency noise to the audio."

Experiment with Evaluation Boards
After engineers refine their search to a few ADCs, they can purchase evaluation boards from ADC vendors and try converters with real-world audio signals. Evaluations might include standard test conditions that companies describe in their device data sheets. The data sheet for a Texas Instruments PCM4222 stereo audio ADC, for example, specifies tests that use System Two Cascade or Cascade Plus test system from Audio Precision as well as Audio Precision filters.

"You can review the Audio Engineering Society's AES17-1998 document, 'AES standard method for digital audio engineering,'" mentioned Martin of TI. "That document explains a variety of standard measurements of audio equipment and data converters. It includes quite a bit of information about how to perform standard audio test on ADCs and DACs. Basically, the standard describes how everyone should measure audio response and operations so people can make equal comparisons."

According to Roche, TI's engineers put a lot of work into evaluation modules so the ADCs behave as described on the data sheets. "If a data sheet states an ADC will offer a 124-dB dynamic range, that's what you can expect from the evaluation board. Customers can use the boards as reference designs, look at the PCB layer stack, and see how we route signals, grounds, and power."

Software Eases System Operations
In addition to providing evaluation boards for most of its products, Wolfson provides evaluation software named the Wolfson Interactive Setup and Configuration Environment, or WISCE, pronounced "whisky." (Wolfson is a Scottish company.) "The Windows-based GUI lets developers click on and set every register in a device," said Scanlan. "You might turn a microphone bias on or off, set the mic gain, turn on a high-pass filter at 250 Hz, and so on. You can click and adjust all the settings before you have integrate the ADC into your circuit."

The WISCE program will create register-setting code in C and add in the register values last used. The C code includes header file for the drivers that run under Linux or Windows CE. During testing, developers can remove a few jumpers on the evaluation board and connect it to a processor for control through an I2C or SPI port. The code loads the register values each time you turn on your system — the ADC does not store them in flash or other memory. Wolfson even recommends the programming procedures to make the register-load steps as "pop" free as possible.

As noted earlier, Microchip offers libraries of audio signal-processing code that runs on its development boards. To be fair, other vendors offer similar libraries, sample code, and development tools. Some software, though, offers a try-before-you-buy option. "We don't think a customer should have to go to a third party, negotiate a license, pay a fee and then get to use the software," noted Microchip's Marsh. "Suppose they try the software and it doesn't solve their problem? Some of our libraries are free and some have a one-time charge, but we don’t charge royalties. Engineers can download a library and if they don’t use it, they don’t pay us. It's basically an honor system."

For further reading

--,"I2S Bus Specifications": www.nxp.com/acrobat_download/various/I2SBUS.pdf [1].

AES17 specification information:
www.aes.org/publications/standards/search.cfm?docID=21 [2]

Baker, Bonnie C.,"Layout Tips for 12-bit A/D Convertors," AN688. Microchip Technology.
www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=1824&appnote=en011698 [3]

Bowling, Steve, "Understanding A/D Converter Performance Specification," AN693. Microchip Technology.
www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=1824&appnote=en011752 [4] (Provides information about ADC parameters.)

"Consumer Audio Market Overview," Texas Instruments.
focus.ti.com/apps/docs/mrktgenpage.tsp?contentId=33731&appId=1

Josefsson, Oli, "Using Sigma-Delta Converters — Part 1," Analog Dialogue, Issue 15.
www.analog.com/library/analogDialogue/Anniversary/15.html [5]

Kester, Walt, "MT-023: ADC Architectures IV: Sigma-Delta ADC Advanced Concepts and Applications," Analog Devices. www.analog.com/en/analog-to-digital-converters/ad-converters/products/tutorials/CU_tutorials_MT-023/resources/fca.html [6]. (Information about idle tones.)

"Solutions for Applications Requiring Audio & Speech Recording/Encoding/Compression." Microchip Technology.
www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=2660&param=en535126 [7]

Macadie, Duncan, "Key Design Considerations for High Quality Audio ADC Performance," WM8781. Wolfson Microelectronics.
http://www.wolfsonmicro.com/uploads/documents/en/Key Design_high quality audio.pdf [8]

Madapura, Jayanth Murthy, "Achieving Higher ADC Resolution Using Oversampling," AN1152. Microchip Technology. www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=1824&appnote=en533730 [9]

Park, Sangil, "Principles of Sigma-Delta Modulation for Analog-to-Digital Converters," APR8/D, Rev. 1. Motorola. www.numerix-dsp.com/appsnotes/APR8-sigma-delta.pdf [10]

Wender, Reid and David Ihme, "How to Design a 16-bit Sigma Delta Analog to Digital Converter," Triad Semiconductor. www.triadsemi.com/2007/01/25/how-to-design-a-16-bit-sigma-delta-analog-to-digital-converter/ [11] (General information about sigma-delta ADCs.)

Links:
[1] http://www.nxp.com/acrobat_download/various/I2SBUS.pdf
[2] http://www.aes.org/publications/standards/search.cfm?docID=21
[3] http://www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=1824&appnote=en011698
[4] http://www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=1824&appnote=en011752
[5] http://www.analog.com/library/analogDialogue/Anniversary/15.html
[6] http://www.analog.com/en/analog-to-digital-converters/ad-converters/products/tutorials/CU_tutorials_MT-023/resources/fca.html
[7] http://www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=2660&param=en535126
[8] http://www.wolfsonmicro.com/uploads/documents/en/Key%20Design_high%20quality%20audio.pdf
[9] http://www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=1824&appnote=en533730
[10] http://www.numerix-dsp.com/appsnotes/APR8-sigma-delta.pdf
[11] http://www.triadsemi.com/2007/01/25/how-to-design-a-16-bit-sigma-delta-analog-to-digital-converter/