SigmaSense®

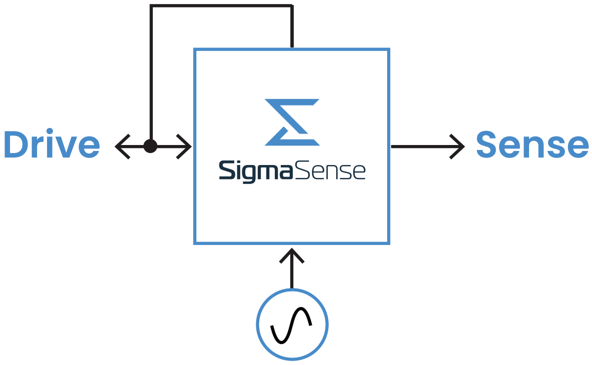
The Reimagined Sigma-Delta

Direct to Digital Sigma-Delta Analog Front Ends (AFE’s)

A REVOLUTIONARY LEAP FORWARD IN SENSING

SigmaSense Redefines the Sigma-Delta

SigmaSense AFE's shift impedance sensing into the digital domain by uniquely converting minute changes in current to digital data. This capability delivers unprecedented improvements in sensitivity and Signal to Noise Ratio (SNR). SigmaSense's proprietary sigma-delta drive-sense circuits offer continuous operation, ultra-low drive voltages, and self-excitation / self-biasing that moves digital sensing much closer to the analog event horizon.



This direct-to-digital approach enables better brick wall noise filtering and additional functions that are software definable. This novel drive-sense capability is called **SigmaDrive**®.

Specifically, SigmaDrive's core architectures support self-referential milli-voltage analog signaling, current domain sensing, frequency division multiple access (FDMA) data mapping, and massive oversampling rates — **on a per channel basis, multi-modal, and continuous**. This combination can yield signal to noise ratios greater than 100x better performance than conventional sensing circuits, when voltage and time are considered. The result is ultra-low power (nano watts per channel) and real-world high sampling and imaging rates. Applications can also natively leverage low voltage digital communications, expanding the future benefits of sharing ultra-high-fidelity data across a broad spectrum of use cases. Applications can use this high-fidelity data to provide a host of new human machine interface (HMI) user experiences that were previously impossible. Machine to machine interfaces can be improved dramatically utilizing this approach as well.

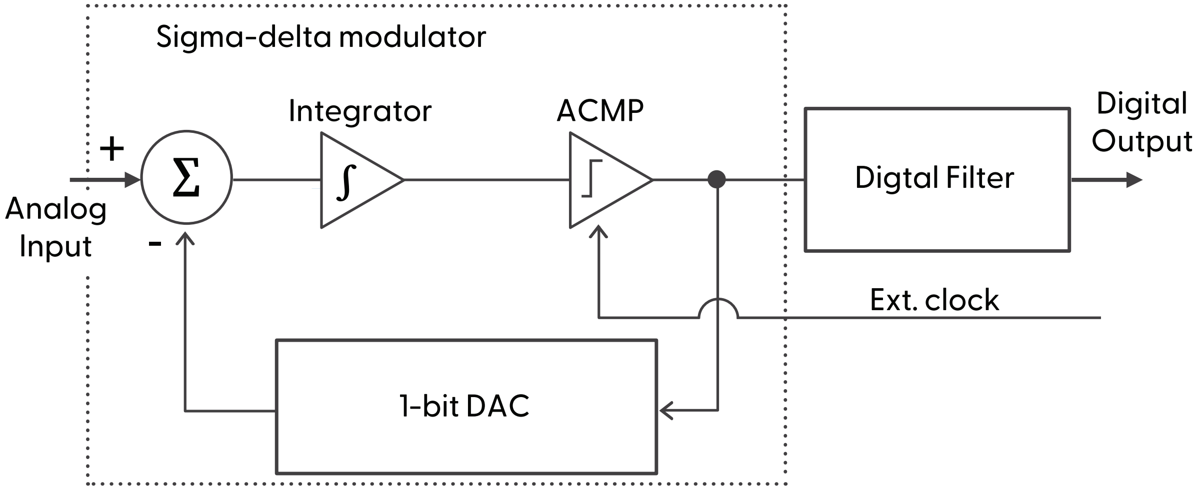
THE TRADITIONAL SIGMA-DELTA

"Delta-sigma (ΔΣ; or sigma-delta, ΣΔ) modulation is a method for encoding analog signals into digital signals as found in an analog-to-digital converter (ADC). It is also used to convert high bit-count, low-frequency digital signals into lower bit-count, higher-frequency digital signals, which is part of the process to convert digital signals into analog as part of a digital-to-analog converter (DAC).

In a conventional ADC, an analog signal is sampled with a sampling frequency and subsequently quantized in a multi-level quantizer into a digital signal. This process introduces quantization error noise. The first step in a delta-sigma modulation is delta modulation. In delta modulation the change in the signal (its delta) is encoded, rather than the absolute value. In delta-sigma modulation, accuracy of the modulation is improved by passing the digital output through a 1-bit DAC and adding (sigma) the resulting analog signal to the input signal (the signal before delta modulation), thereby reducing the error introduced by the delta modulation.

Both ADCs and DACs can employ delta-sigma modulation. A delta-sigma ADC first encodes an analog signal using high-frequency delta-sigma modulation, and then applies a digital filter to form a higher-resolution but lower sample-frequency digital output. A delta-sigma DAC encodes a high-resolution digital input signal into a lower-resolution but higher sample-frequency signal that is mapped to voltages, and then smoothed with an analog filter. In both cases, the temporary use of a lower-resolution signal simplifies circuit design and improves efficiency.

Primarily because of its cost efficiency and reduced circuit complexity, this technique has found increasing use in modern electronic components such as DACs, ADCs, frequency synthesizers, switched-mode power supplies and motor controllers." (Credit Wikipedia.)

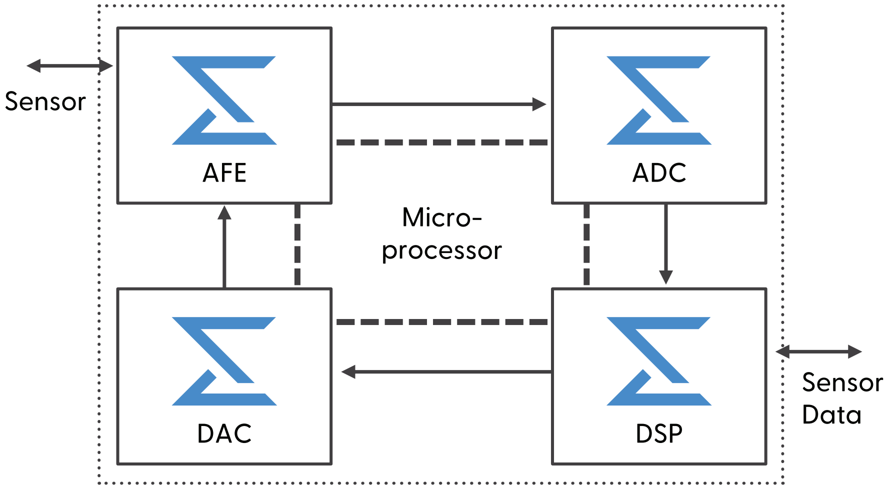


Traditional Sigma-Delta Modulator

THE SIGMASENSE SIGMADRIVE APPROACH

SigmaDrive uses highly modified sigma-delta architectures with an advanced current drive feedback loop to overcome the limitations of traditional impedance-based sensors. It offers self-excitation, multi-modality concurrent sampling, and simultaneous operation of all channels in an array. This low-cost low-power digital architecture provides excellent noise rejection and a significantly improved signal-to-noise ratio.

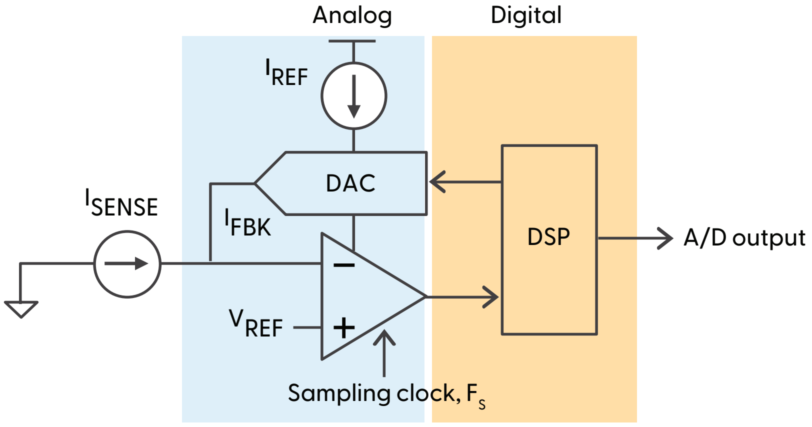
SigmaDrive encompasses 4 primary analog and digital functions integrated into one channel, each **on a single pin.**



4-in-1 Single Channel Architecture

When implemented in large arrays, these fully integrated drive and sense functions yield “large array frequency analysis” in a small silicon package. This capability captures the data direct-to-digital and can be thought of as a network analyzer on each channel. A SigmaSense SDC-200 ASIC supports 128 SigmaDrive channels, DSP, and micro-processing in a very small BGA package.

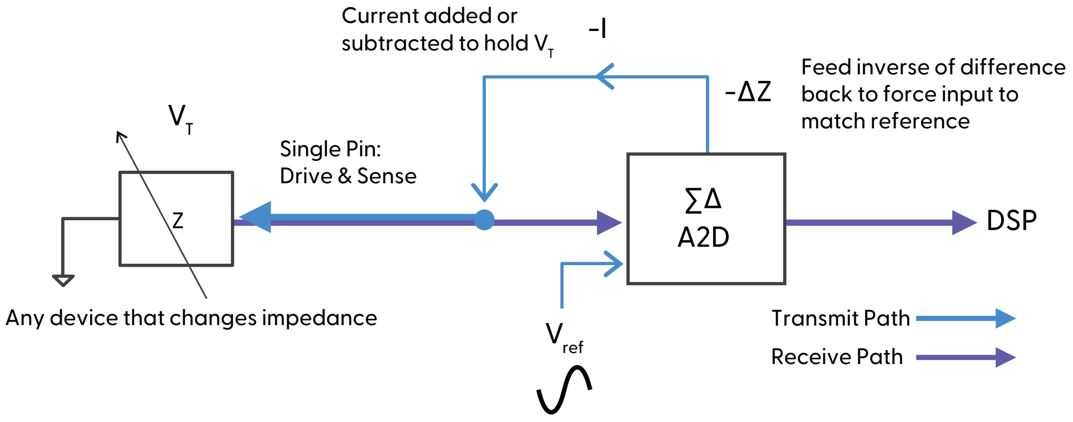
The diagram below shows a simplified SigmaDrive channel and the analog / digital boundary. The SigmaDrive architecture is roughly 92% digital in contrast to standard traditional A to D and D to A architectures at approximately 40% digital. The result is digital scalability with expanded control over a greater number of software-defined variables.



SigmaSense SigmaDrive Modulator – Simplified

SigmaDrive fundamentally exceeds the capabilities of the customary sigma-delta designs by using self-excitation and self-biasing, as well as a current feedback loop on every channel for sensing functions. Because of the closed loop and continuous nature of the SigmaDrive sigma-delta modulator, current for (I_{SENSE}) is digitized by a comparator over-sampled at clock F_S. The DSP reads the comparator output and controls the DAC to keep the feedback current (I_{FBK}) following (I_{SENSE}) at the comparator negative terminal at (V_{REF}). The DSP provides the A to D conversion for which the digital full scale is equivalent to (I_{REF}).

Below is a simplified flow block diagram of the diagram above for additional clarity. This current drive architecture has no traditional V to I conversion, and all 4 primary functions noted above happen concurrently and continuously on a single pin.



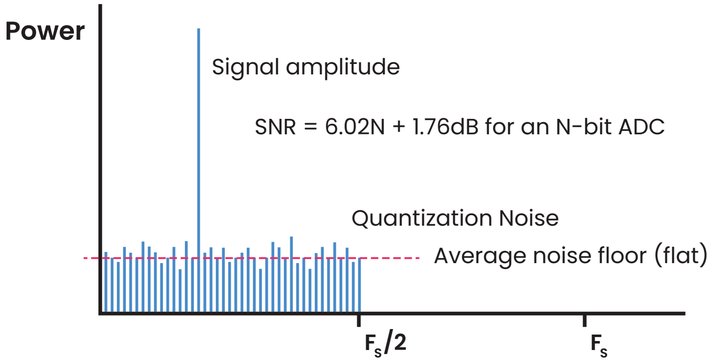
SigmaDrive Functional Flow Block Diagram

Since an NCO (numerically controlled oscillator) reference is used to generate one or many noise-shaped pure-tone drive signals, digital data can be encoded on the (VREF) for information transmission at high resolution. This capability opens new applications for device-to-device communications or using the body or another conductor as a network.

OVER SAMPLING

Frequency spectrum a conventional ADC with a sampling frequency F_S.

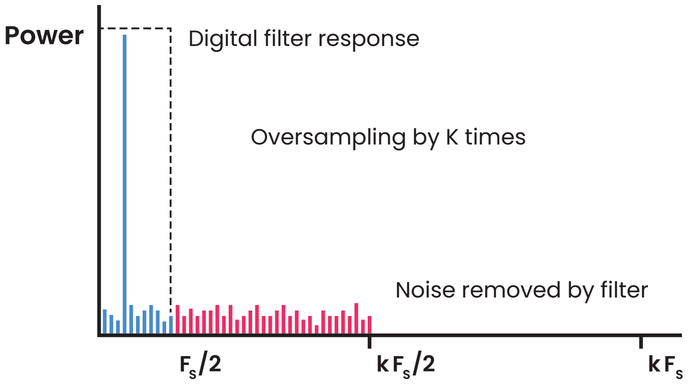
The image to the right shows the frequency-domain transfer function of a traditional multi-bit ADC with a sine-wave input signal. The SNR, which is the difference between the signal amplitude and the average noise floor from quantization, is calculated as SNR = 6.02N + 1.76dB where N is the number of bits. In a conventional ADC, SNR can be improved by increasing the number of bits but that adds cost and complexity.



The Frequency Domain

Another technique for improving SNR is to oversample the signal by a factor of k times. Oversampling has the effect of spreading the quantization noise through a wider spectrum thereby reducing the noise floor in the frequency band of interest. It can be shown the there is a 3dB reduction in quantization noise for every 2x oversampling. This improvement can effectively enhance the effective number of bits (ENOB) by 1bit for every 4x oversampling. Sigma-delta converters employ a simple 1-bit ADC that can easily oversample the input signal by 4x thereby improving the SNR by 6dB (1 ENOB). The Sigma-delta converter can be software controlled to use any digital filter needed to further improve noise rejection.

Effect of over-sampling and digital filtering.



The Digital Filter

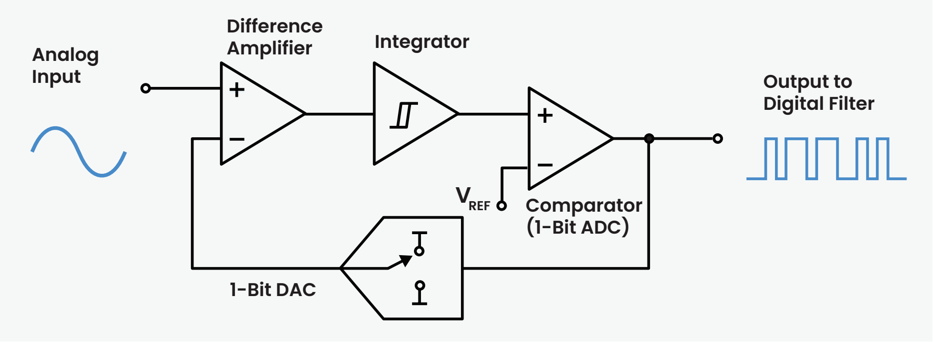
In theory, a designer could oversample at the appropriate rate k to achieve the desired signal resolution. But in practice, this is not achievable. For example, it is possible to increase the signal resolution of a 4-bit ADC to 12 bits.

The result is 1 ENOB for every 4x oversampling so to get another 8 bits, we would increase the original sample rate by 4^8 = 65536 times.

Note: Sigma-delta converters overcome this limitation with the technique of noise shaping resulting in a SNR improvement of more than 6dB for each factor of 4x oversampling.

SNR IMPROVEMENT WITH NOISE SHAPING & DIGITAL FILTERING

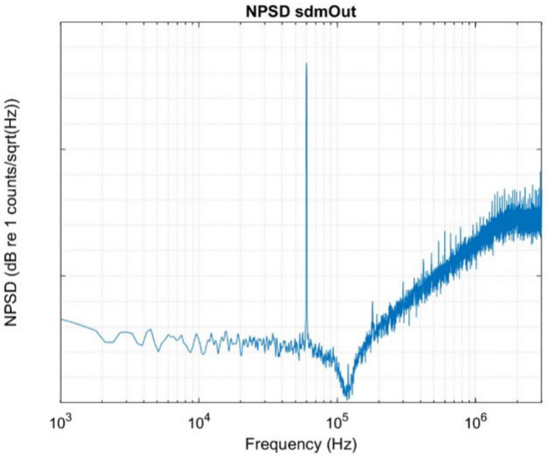
To understand noise shaping, consider the block diagram of a first-order sigma-delta modulator shown in the following diagram. It consists of a difference amplifier, an integrator, and a comparator with feedback loop that contains a 1-bit DAC that keeps the average output of the integrator near the comparator's reference level. The mismatch between the DAC output and the signal input creates an error signal input at the output of the difference amplifier. The Sigma-delta architecture oversamples an analog signal and produces a fast stream of ones and zeros at the output of the modulator. The density of ones is proportional to the input signal. As the input signal increases, the density of ones increase, and as the input signal decreases, so does the density of ones.



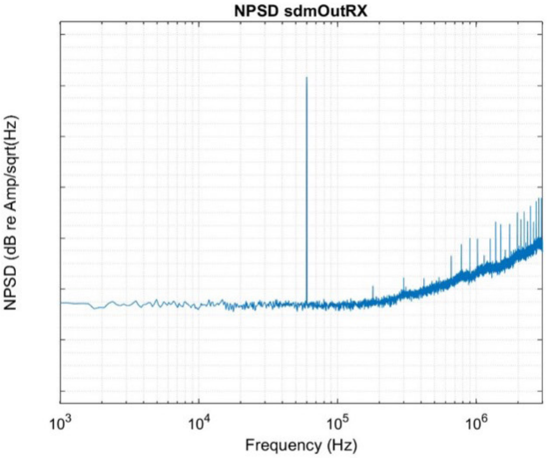
Above, the integrator functions as a low-pass filter to the input signal and a high-pass filter to the quantization noise. Therefore, as previously mentioned, the frequency transfer function of the quantization noise is different than that of the input signal. The effect is to push the quantization noise into higher frequencies. This noise shaping is depicted below, which shows the real-time frequency spectrum of the output of a Sigma-delta modulator. The noise power has not changed but its distribution has.

Powerful digital filtering techniques can be applied to the noise-shaped delta-sigma modulator that removes even more noise than does simple oversampling as shown below. A significant advantage of the digital filter is that we can design it to an optimal configuration for power and noise rejection. No other PCAP system matches the performance of SigmaDrive in stability and noise immunity.

TRANSMIT

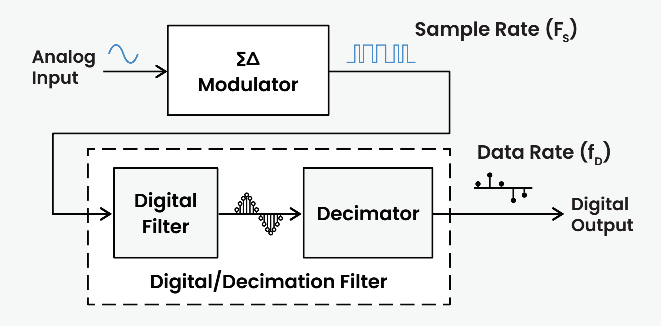


RECEIVE



The Sigma-delta modulator in the following diagram provides a 9dB improvement in SNR for every doubling of the sampling rate. So far, we have only discussed a first order Sigma-delta modulator. Higher order modulators are achieved by adding more integration stages, which results in more aggressive noise shaping. This gives better noise filtering in the frequency band of interest and further improves SNR. For example, a second-order sigma-delta modulator provides a 15dB improvement in SNR and a third-order modulator provides a 21dB improvement in SNR for every doubling of the sampling rate. A designer can choose a target SNR simply by exploiting this relationship between over-sampling ratio and the order of the sigma-delta modulator.

The output of the digital filter is a high-resolution representation of the analog input signal that is at the over-sampling data rate. A decimator function, in accordance with the Nyquist criterion, is applied to the digital filter output so that the final output data rate, fD, is more manageable.



IMPEDANCE AS A FUNCTION OF FREQUENCY

The use of sinusoidal AC waveforms enables the SigmaDrive to not only serve as a sensor controller but also an impedance analyzer. The drive transmits an AC voltage at a set amplitude, frequency and phase into the load while simultaneously measuring the associated load current. The load current is digitally acquired via the methods above and is passed to a block that performs a Discrete Fourier Transform (DFT). The DFT is also known as an IQ Demodulator since the DFT breaks the acquired current signal into its real (I) and imaginary (Q) components. Once the IQ components are obtained, magnitude and phase of the complex impedance can be calculated. This ability to characterize a sensor's impedance as a function of frequency is an important feature of the SigmaSense technology.

For example, this capability allows for the capacitive dominant region of a touchscreen's impedance to be characterized, thus ensuring the controller operates in a band where the sensitivity is maximized. Another example is where the precise measurement of a pressure sensor's resistive dominant impedance region is used for force sensing while the capacitance region of impedance is used for sensor health and base-lining – this is all done on one pin concurrently with one, many, or sweeping frequencies.

Manufacturers can now characterize and track a sensor's impedance in a production setting as well as monitor its aging or other operational conditions such as damage. This full spectrum impedance measurement capability brings new toolsets to sensor sub-system design.

WHY IS CONTINIOUS DRIVE ADVANTAGEOUS OVER SWITCHING. IT'S ALL ABOUT TAU.

Tau is the time constant of an RC circuit that it takes to change from one steady state condition to another steady state condition when subjected to a step change input condition.

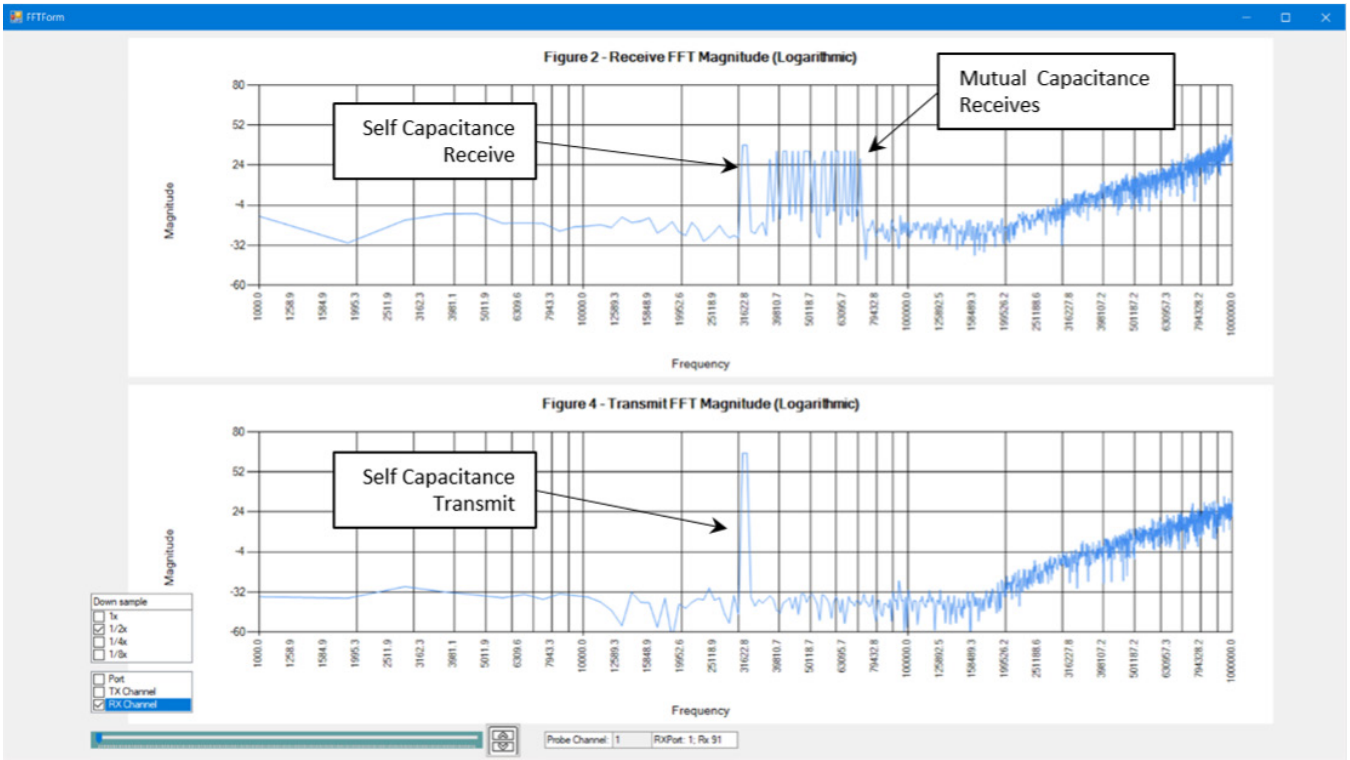
Why is this relevant? Electronic circuits are not always in a stable or steady state condition but can be subjected to sudden step changes in the form of changing voltage levels or input conditions. For example, the opening or closing of an input or output switch.

However, whenever a voltage or state change occurs, a circuit with capacitive and/or inductive elements cannot respond instantaneously and will require time to reach a stable state. The change of state from one stable condition to another generally occurs at a rate determined by the time constant of the circuit which itself will be an exponential value with an exponential decay. The time constant of the circuit will define how the transient response of the currents and voltages are changing over a set period of time.

Sensor arrays such as switched capacitive touch systems can only run as fast as the system can switch, settle, and sample. The SigmaDrive architecture operates continuously on every channel mitigating the effects of system RC timing constraints.

As an example of RC timing mitigation, the image below shows one column of continuous data from a SigmaSense capacitive imaging system. In this case, a column self-capacitance transmit frequency in the lower DFT plot shows a high SNR sinusoidal with noise shaping. The top DFT plot shows its corresponding received self-capacitance frequency plus all the mutual-capacitance receive frequencies transmitted from the adjacent rows. This continuous and concurrent operation allows for the change of impedance impact on both self and mutual capacitances to be measured simultaneously without switching. Additionally, any other frequencies carrying data such as active pens will also be measured concurrently.

Continuous data refresh rates of 600hz and higher are possible by the SigmaDrive architecture.



Down sample
☐ 1x
☑ 1/2x
☐ 1/4x
☐ 1/8x

☐ Port
☐ TX Channel
☑ RX Channel

Probe Channel: 1
RXPort: 1; Rx 91

Continuous channel response of PCAP self-transmit (bottom) and self-receive plus row mutual-receives (top)

***Note the high SNR and noise shaping.**

DYNAMIC NOISE AVOIDANCE

A system running SigmaDrive concurrently on every channel can be configured to continuously sample one, many, or all channels to determine if any noise is getting past the filters. The data from adjacent channel DFTs can be used to inform the system where the noise resides in the frequency spectrum before triggering a command to move the drive frequency elsewhere or skip it completely. The ability to see and avoid environmental and system noise, combined with high-frequency filtering of quantization noise, and DSP narrow band filtering of the source frequency, results in a Sigma-Delta circuit with the highest SNR in the industry.

SigmaSense's Capacitive Imaging operational theory is discussed in greater detail in the **"Capacitive Imaging Using Impedance Spectroscopy"** white paper.

CONCLUSION

SigmaSense has redefined analog sensing. With the development of a reimagined Sigma-Delta architecture, radical improvements are made in sensitivity and SNR. These consequential improvements are a result of a four-fold approach: a redefinition of the Sigma-Delta architecture, removal of quantization noise inherent in Sigma-Delta techniques, aggressive narrowband DSP filtering, and dynamic noise avoidance made possible through spectral analysis. Furthermore, our direct-to-digital approach removes the additional power-hungry analog pre-processing circuitry found in typical AFEs leading to a 90% digital chip that is smaller, lower cost and lower power.

While technologies exist for general sensing applications, manufacturers today need new sensing capabilities to solve difficult problems and enable better outcomes for the manufacturer and the end user. For system designers, sensitivity, noise rejection, high SNR and low power consumption are paramount. SigmaDrive is the solution to these challenges.

New experiences require new sensing features that are not available today. The extensive capabilities of SigmaSense's technology makes possible future devices that deliver on designer needs and feature innovative user experiences.

SigmaSense®