WHITEPAPER

SmartEdge^{TM} Platform – Calibration and Measurement Accuracy

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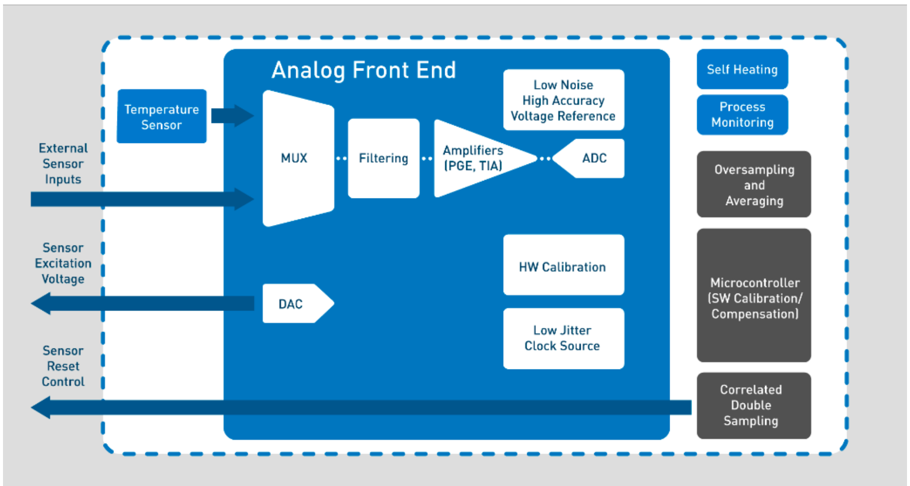
Introduction

The rapid acceptance of the Internet of Things is accelerating the growth of sensors connecting the physical world to the digital world. In the past, all this information was being processed at the cloud. The big driver is now with regard to edge computing and the requirement to process the data at the sensor edge. This is adding a lot of intelligence at edge node and in order to perform accurate sensor measurements here, it is necessary to perform some level of calibration.

Calibration must typically be applied to both the External Sensor and the Analog Front End, the example signal chain below shows the main components of a typical Analog Front End.



In addition to calibration there are other schemes that can compensate for measurement inaccuracies, these will be discussed in the relevant sections below.

Calibration of Analog Front End (AFE)

Voltage Reference

The Voltage Reference is the first element that can impact sensor measurement accuracy since the majority of Analog Front End components are dependent on a Voltage Reference (e.g. ADC).

To reduce noise, improve voltage accuracy and improve temperature stability the Voltage Reference is typically one-time calibrated during silicon manufacturing to compensate for process variations and devices mismatches.

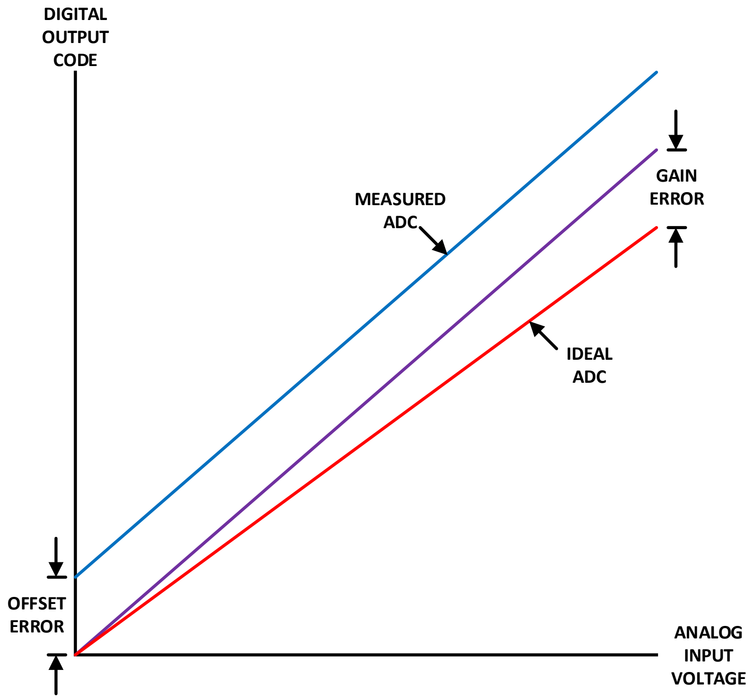
Depending on the sensor type it may be possible to use a ratiometric measurement scheme, in this case Voltage Reference errors are mostly removed because the same signal that excites the sensor is used as the reference voltage for the AFE.

Analog to Digital Converter (ADC)

The ADC is the next element that needs to be considered with respects to sensor measurement accuracy.

Offset Error and Gain Error

The primary characteristics of an ADC that affect data conversion accuracy are offset error and gain error. For example, both offset error and gain error can lead to an inaccurate measurement of a battery voltage leading to an incorrect estimation of the remaining battery life.



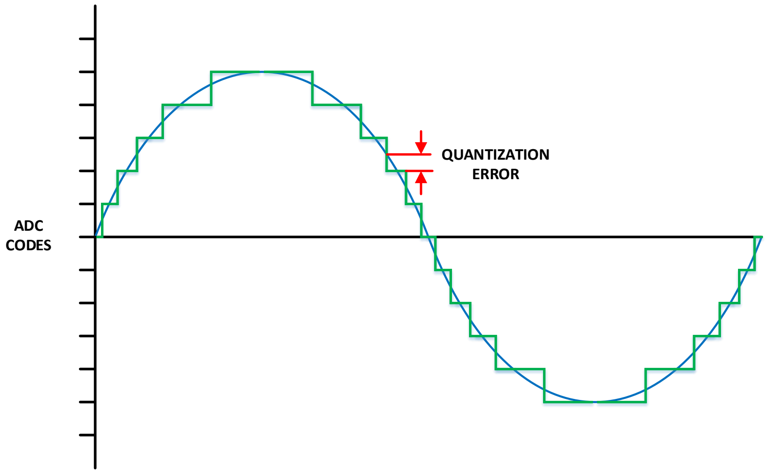
ADC typically contain a self-calibration feature that is executed on power-up to compensate for process variations and devices mismatches, as well as reducing offset error and gain error. If an ADC lacks the self-calibration feature, the offset error and gain error can be calculated by measuring 2 known reference voltages (Two Point Calibration) and the ADC digital code can be corrected by applying the appropriate compensation factors to the digital measurements through software.

The offset error and gain error typically vary with temperature and the above compensation schemes are only carried out at a fixed temperature.

If an application is sensitive to temperature drift the self-calibration feature can be periodically executed during run-time to ensure the change in offset error and gain error does not impact the accuracy of the measurements. If an ADC lacks the self-calibration then compensation factors will need be calculated at several temperature points and software can then use a temperature sensor to select the appropriate compensation factor to apply.

Quantization Error

The normal operation of an ADC will always lead to inaccuracies because of the effects of quantization. An example of quantization error or noise for a low-resolution ADC is shown in the diagram below.



The magnitude of the quantization error is inversely proportional to the chosen ADC resolution (e.g. 12-bit). Increasing the resolution is one way of improving the accuracy of the quantized signal but there are diminishing returns as the complexity of the ADC increases significantly.

For example, the effect of 12-bit (4096 level) quantization on a full-scale input signal of 1.2V is minimal since the quantization error is at most ±0.5 of a code width (LSB) or ±146µV (1.2V / 8192) which equates to ±0.012%. However, for a low amplitude input signal of 3mV this error is significant and equates to ±4.8%.

It is not necessary to increase the ADC resolution to ensure accurate conversation of low amplitude signals and instead signal conditioning schemes, such as those described later in this document, can be used to make best use of an ADCs dynamic range.

Aperture Jitter

Aperture jitter is another contributor to measurement inaccuracies. Aperture jitter is the variation in aperture delay for successive samples and has the main consequence of degrading the Signal-to-Noise Ratio (SNR) of the ADC when sampling relatively high frequency input signals.

However, this effect cannot be fixed by calibration but careful selection of appropriate components can minimize the effect. The jitter of the clock into the ADC can be a significant contributor to the aperture jitter so choosing a low jitter clock source is important to ensure accurate measurements of such signals.

The assumption made to guarantee that the voltage error due to jitter is tolerable, is to assure that it is smaller than half of a code width (LSB). Assuming a full-scale sinusoidal input signal, the max allowable jitter (σ) can be calculated as follows:

$$\sigma \ = \frac{1}{(\pi * F_{IN} * 2^{N} + 1)}$$

Where N is the ADC resolution and F_{IN} is the input signal frequency. For example, a 1MHz full-scale input signal that is sampled by a 12-bit ADC will result in a max allowable jitter of 38ps.

It is good design practice to specify a jitter budget well below the calculated threshold to account for nonidealities present in any real design.

Signal Conditioning

Signal Conditioning is an analog pre-processing step carried out before data conversion.

Low amplitude signals from a sensor can be amplified to minimize quantization noise by spreading the signal across the full dynamic range of the ADC. A Programmable Gain Amplifier (PGA) is typically used to provide this capability.

Filtering techniques can also be employed to improve conversion accuracy. For example, DC Offset Filtering to ensure PGA output can cover the full dynamic range and Low Pass Filtering to remove high frequency noise.

Oversampling and Averaging

Oversampling and Averaging is a digital post-processing step carried out after data conversion.

Under the correct conditions (primarily input signals with white noise with amplitude greater than 1 LSB), oversampling of an input signal and averaging the resulting ADC outputs can be used to effectively increase the ADC precision and improve the Signal-to-Noise Ratio (SNR).

For n additional bit(s) of resolution the signal must be oversampled 4^n times with an average calculated across the 4^n samples. For example, a 14-bit ADC must be oversampled 16 times to achieve 16-bit resolution.

Programmable Gain Amplifier (PGA)

A Programmable Gain Amplifier is a voltage-to-voltage converter that is used to amplify the input voltage of a sensor signal by a selectable gain.

Like the ADC the primary characteristics of a PGA that affect signal amplification accuracy are offset error and gain error.

The offset error and gain error can be calculated by measuring 2 accurate and stable reference voltages (Two Point Calibration) and applying the appropriate compensation factors to the resulting ADC digital measurements through software.

The offset error and gain error vary with temperature and the above compensation scheme is typically only carried out at a fixed temperature.

A form of Correlated Double Sampling (CDS) can be used if an application is sensitive to temperature drift of the PGA offset error. Prior to every measurement of the input signal, a measurement is taken by connecting the input of the amplifier to ground. This measurement provides the offset error and this is then used to correct the subsequent signal measurement (subtraction).

A highly accurate External Reference Voltage which has very low temperature coefficient can be used if an application is sensitive to temperature drift of the PGA gain error. Prior to every measurement of the input signal, a measurement is taken by connecting the input of the amplifier to the External Voltage Reference. This measurement provides the information necessary to calculate the gain error and this is then used to correct the subsequent signal measurement (scaling).

Transimpedance Amplifier (TIA)

A Transimpedance Amplifier is a current-to-voltage converter that is used to amplify the input current of a sensor signal. A TIA is typically used when the current response of a sensor is more linear than the voltage response.

Like the ADC the primary characteristics of a TIA that affect signal amplification accuracy are offset error and gain error.

The offset error and gain error can be calculated by measuring 2 accurate and stable reference currents (Two Point Calibration) and applying the appropriate compensation factors to the resulting ADC digital measurements through software.

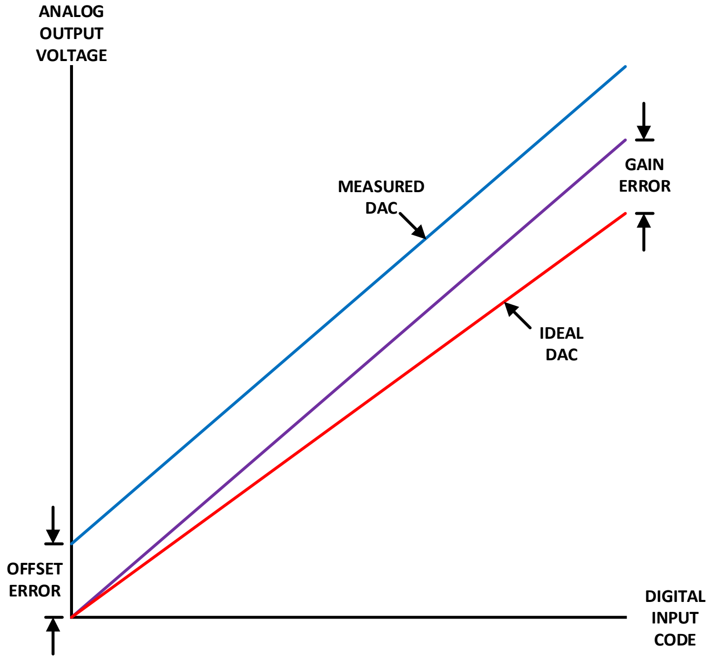
The offset error and gain error vary with temperature and the above compensation scheme is typically only carried out at a fixed temperature.

Two highly accurate External Reference Currents (e.g. from a Current-Output Digital to Analog Converter) which have very low temperature coefficient can be used if an application is sensitive to temperature drift of the offset and gain error. Periodic measurements of the External Reference Currents can be used to dynamically determine the offset error and gain error and correct subsequent signal measurements.

Digital to Analog Converter (DAC)

It is common for a DAC to be used to send excitation signals to a sensor. Errors in the DAC output will inevitably translate to errors in the measured signal back from the sensor.

Like the ADC the primary characteristics of a DAC that affect output accuracy are offset error and gain error.



In some cases, the DAC output will go through some form of analog signal conditioning that may allow compensating for the offset error and gain error.

Alternatively, digital correction can be applied as follows:

1. Offset error and gain error can be calculated by measuring the voltage corresponding to two DAC codes (Two Point Calibration) and comparing to the expected voltage.
2. Based on the calculated errors the appropriate compensation factors can be applied to the DAC code to create a digital code that will result in a voltage closer to the expected voltage.

The offset error and gain error typically vary with temperature and compensation schemes are only carried out at a fixed temperature.

If an application is sensitive to temperature drift then compensation factors will need be calculated at several temperature points and software can then use a temperature sensor to select the appropriate compensation factor to apply.

Process Monitoring

It is common and expected that the silicon device characteristics will vary from part to part due to process variations during manufacturing. The primary characteristics of interest are typically the Resistance (R) and Capacitance (C).

If the chosen measurement scheme is sensitive to variation in the above characteristics the Process Monitoring Block can be used to determine the R and C characteristics of the part enabling appropriate compensation to be applied.

Self-Heating

In certain situations, it may be necessary to control the temperature of the silicon to minimize the effects of temperature on measurements.

A Self-Heating Block can be used to modulate the current consumption within the device to ensure the silicon temperature remains stable during measurements and consequently results in lower measurement error.

Calibration of External Sensors

No sensor is perfect and manufacturing variations mean that even two sensors from the same manufacturer production run may yield slightly different readings. As a result, calibration is required to ensure consistent measurement accuracy.

The typical characteristics of External Sensors that impact measurement accuracy are offset error, gain error, nonlinearity and Hysteresis.

Different calibration schemes can be applied depending on the functional behaviour of the sensor and the nature of the errors and inaccuracies that the sensor is exposed to. The most common calibration schemes are discussed below.

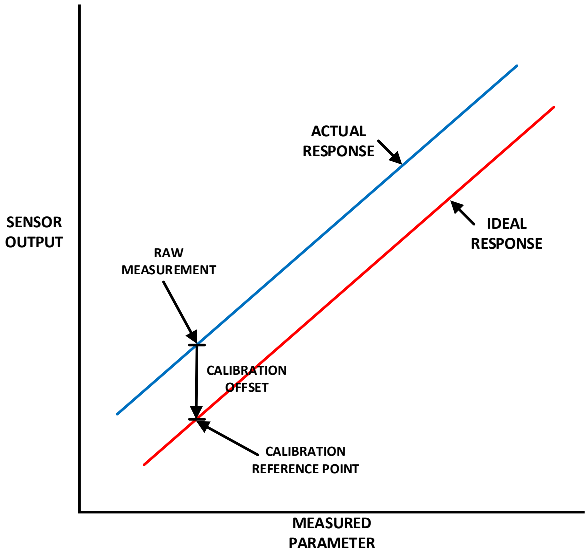
In some situations, it may be possible to calibrate the entire system in one go e.g. DAC + External Sensor + PGA + ADC. However, if a single ADC is used with multiple sensors of different type this will not be possible due to the varying error characteristics of those sensors.

One Point Calibration

One Point Calibration is simplest type of sensor calibration. One Point Calibration is useful in the following cases:

- The application only requires accurate measurement of a single level, e.g. application is interested in the temperature reaching a fixed threshold
- The sensor response is known to be linear and has the correct slope (i.e. no gain error) over the desired measurement range

This involves taking a measurement of a single calibration reference point.

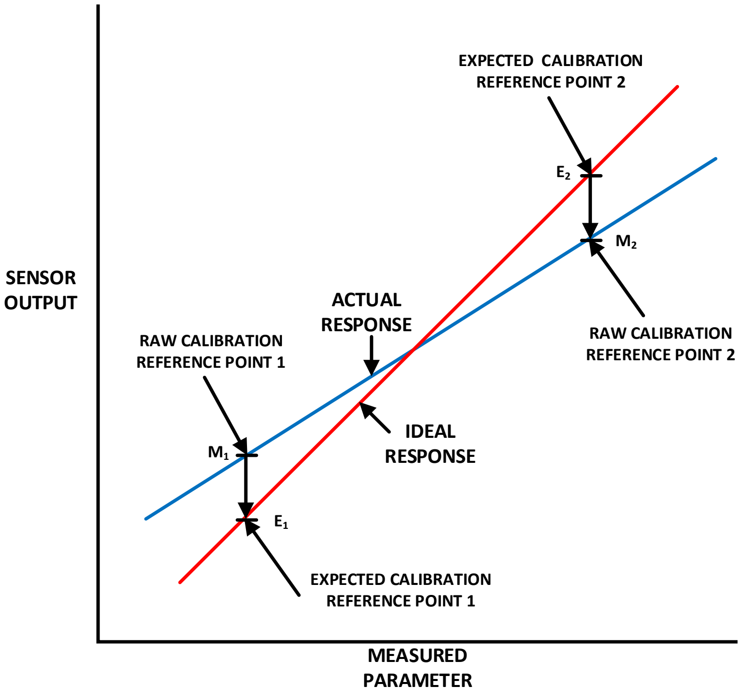


The measured Calibration Offset parameter corresponding to the calibration reference point can then be used to compensate for the offset error of subsequent measurements.

Two Point Calibration

Two Point Calibration is a little more complex. Two Point Calibration is useful when the response is known to be linear over the desired measurement range but both offset error and gain error (incorrect slope) are present.

This involves taking measurements for two calibration reference points (low and high) that cover the measurement range.



The measured parameters corresponding to both calibration reference points can then be used to compensate for the offset error and gain error of subsequent measurements. The following calculation is used to correct the sensor sample measurement:

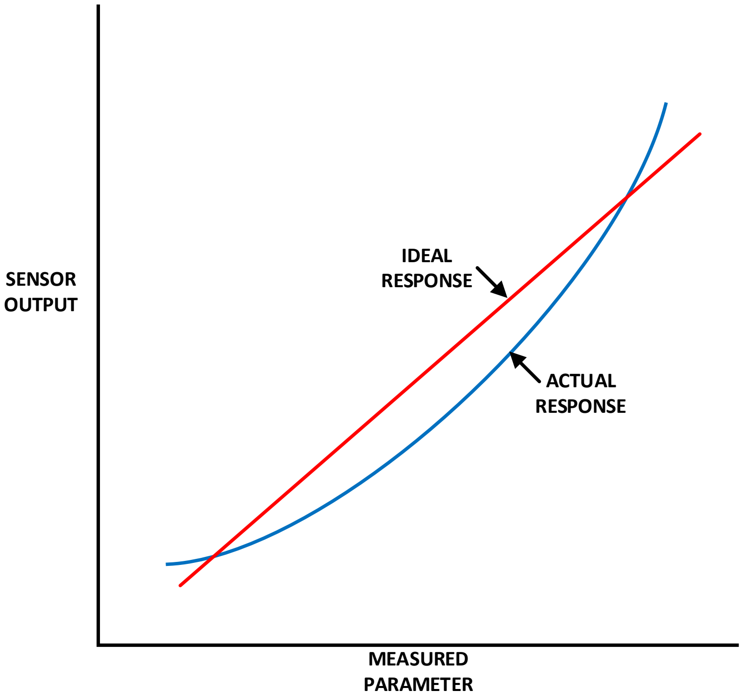
$$Corrected\ Sample = \frac{(M_s - M_1) * (E_2 - E_1)}{(M_2 - M_1)} + E_1$$

Where M_S is the raw sensor sample measurement, M_1 & M_2 are the raw calibration reference point measurements and E_1 & E_2 are the expected calibration reference point measurements.

Multi-Point Calibration (Curve Fitting)

Multi-Point Calibration is more complicated again and is required when the sensor response is not linear over the measurement range. This typically requires curve fitting to compensate for the nonlinearity. Offset error and gain error are also compensated for with this scheme since more than two calibration measurements are required to enable curve fitting.

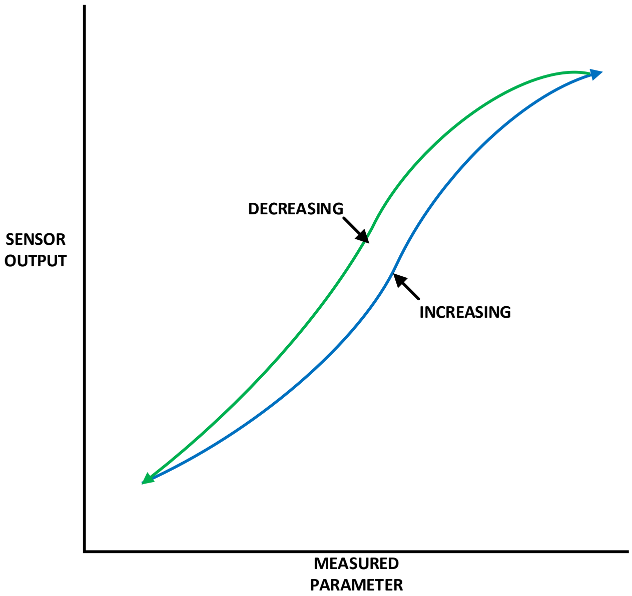
This typically involves taking measurements for multiple calibration reference points that cover the measurement range.



With sufficient measurements the curve-fitting coefficients for the characteristic curve of the sensor can be calculated. Those coefficients feed into the linearization formula used to compensate for the errors in the sensor measurement.

Sensor Response Hysteresis

Some sensor types with non-linear response also exhibit hysteresis. For example, the sensor reads low with an increasing signal and high with a decreasing signal as shown in the diagram below.



If the hysteresis effect is tolerable a single characteristic curve for the nonlinearity can be determined that is a close fit to both curves and used to derive the linearization formula for the sensor.

However, if the hysteresis effect is not tolerable two linearization formula need to be derived for the sensor with a one formula used for an increasing signal and the other used for a decreasing signal. This requires analysis of prior sensor readings to determine the signal “direction”, those sensor readings need to be taken at sufficiently regular intervals to ensure “direction” changes are not missed.

Effects of Temperature Drift

The above calibration schemes are carried out a fixed temperature. However, it is common for the sensor characteristics to vary with temperature.

If an application is sensitive to temperature drift the calibration algorithms above need to be ran at different temperatures to create a set of compensation variables that can be applied based on the temperature at the time of measurement. This requires the use of a temperature sensor in the silicon to look-up the appropriate compensation variables.

With limited measurements, it may be necessary to extrapolate the compensation variables. For example, if the temperature is 35°C and there are compensation variables for 30°C and 40°C the average of both sets of compensation variables could be used.

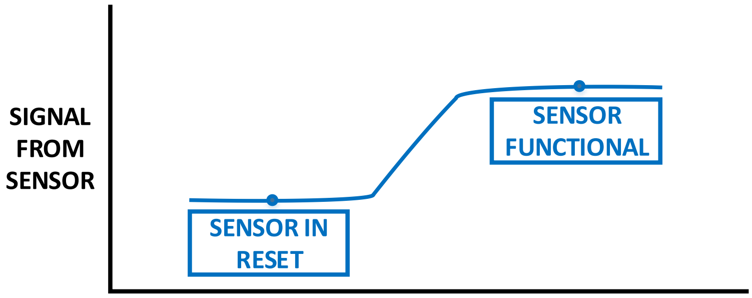
Effects of Aging

Certain sensors may exhibit an aging effect. A periodic One Point Calibration can be carried out to detect changes in characteristics due to aging and trigger re-calibration of the sensor. Alternatively, if the aging effect is well understood the existing compensation variables can be modified to account for the aging effect.

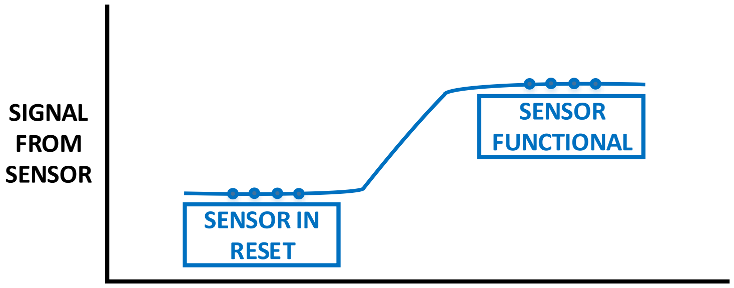
Correlated Double Sampling (CDS)

Correlated Double Sampling (CDS) can be used to dynamically remove offset error in addition to reducing the effect of low-frequency noise for sensors that support being put in a reset state

Prior to measuring the input signal, a measurement is taken when the sensor is in reset. The reset measurement is subtracted from the signal measurement resulting in the removal of the offset error and reduction in the low-frequency noise.



Under the correct conditions the Oversampling and Averaging technique described previously can be employed to provide further noise reduction. In this scheme, multiple measurements are taken of both the reset level and the signal level, the resulting output is the difference of the average of the signal measurements and the average of reset measurements.



S3 Semiconductors SmartEdge^{TM} Platform

S3 Semiconductors have a wide range of IP including Bandgap Refences, Analog to Digital Converters, Digital to Analog Convertors, Programmable Gain Amplifiers and Low-Jitter PLLs that can be integrated in your custom silicon to meet the accuracy requirements of an Analog Front End.

S3 Semiconductors SmartEdge^{TM} platform incorporates all the Sensor AFE (Analog Front End), Calibration, Control, Security and Industrial Communication elements of a smart edge device, all integrated onto a single cost-effective chip. With more than 20 years' experience designing advanced embedded mixed-signal chips for hundreds of customers in every major region, S3 Semiconductors delivers a new breed of design-centric semiconductor supplier capable of optimising its designs for every customer, yet achieving cost economies not thought possible with custom chips designs until now