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APPLICATION NOTE 3650

The MAX1464's On-Chip Temperature Sensor

Abstract: The MAX1464, a high-performance digital signal conditioner, includes an internal temperature sensor that can be used to correct temperature-dependent signals or as a stand-alone thermometer with comparable performance to the industry's leading temperature sensors. This application note describes the MAX1464 on-chip temperature sensor and suggests ways to achieve temperature readings that approach repeatability of the test system.

Introduction

The MAX1464 is a high-performance digital signal conditioner with an on-chip temperature sensor that outputs approximately +2mV/°C over its wide -40°C to +125°C operating temperature range. A built-in 16-bit ADC converts the internal temperature-sensor output in a similar manner to the sensor inputs. While converting the temperature-sensor output, the ADC (ADC_T for temperature sensor output) automatically uses four times the internal band-gap voltage (4 x 1.25V = 5V) as the ADC_T reference voltage. The temperature data format is 15-bit plus sign-bit in two's-complement. For improved temperature resolution, the MAX1464's Coarse Offset (CO) DAC can be programmed to zero the temperature-sensor output offset and PGA gain can be programmed to amplify the temperature sensor output. The internal CPU can be used to provide additional digital gain and offset correction.

Compared to its predecessor, the MAX1463, the MAX1464 significantly improved the ratiometric error (or power supply rejection ratio, PSRR) of the on-chip temperature sensor. This application note quantifies the MAX1464's PSRR as very small error, and presents a simple equation to reduce that error by another 75%.

Calculating the Temperature-Sensor Output Values

Table 1 presents normalized MAX1464 temperature-sensor output for 50 representative samples for V_{DD} values of 4.5V, 5.0V, and 5.5V with COT[3:0] = 1101 and PGAT[4:0] = 00001 (PGA gain = 7.7). (Higher PGA gains will cause the ADC to saturate which would result in invalid values.) As Table 1 shows, the typical ADC_T output swing for the -40°C to +125°C temperature range is 0.4830 normalized ADC value (approximately 16,000 ADC counts) at V_{DD} = 5V. Consequently, in our analysis, we used the 0.4830 value as the temperature-sensor full-scale output to represent the temperature-sensor errors as percent of full scale (%fs). In real-world applications, you can use the MAX1464's internal CPU to apply additional digital gain and offset adjustment to the temperature-sensor output and thus obtain a calibrated temperature output. The application note, MAX1464 Signal-Conditioner, Sensor Compensation Algorithm, demonstrates this use of the CPU.

Table 1. Normalized ADC Readings on the MAX1464

Supply Voltage	Typical Temperature-Sensor output (PGAT[4:0] = 00001; COT[3:0] = 1101)						V_{DD}[1,2]
	-40°C	0°C	+25°C	+70°C	+85°C	+125°C	+70°C
4.5V	-0.26218	-0.14002	-0.08126	0.06909	0.11344	0.22223	0.61602
5.0V	-0.26384	-0.14195	-0.08328	0.06671	0.11097	0.21912	0.68393
5.5V	-0.26480	-0.14311	-0.08451	0.06516	0.10936	0.21684	0.75118

1- The MAX1464 automatically applies a gain of 0.7 when using the ADC to convert V_{DD}

2- Only PGA[4:0] = 00000 will produce a valid result when reading V_{DD}. A higher gain setting will cause the ADC to saturate.

Calculating and Optimizing PSRR

The MAX1464's on-chip temperature sensor was originally intended for sensor compensation only. For this purpose, absolute accuracy, or lack of it, is inconsequential to the end product. Temperature-sensor repeatability and ratiometric error are, however, significant for the end product's performance. The MAX1464's on-chip temperature sensor has excellent repeatability. The largest standard deviation for 100 readings of discrete temperature point between -40°C and +125°C was only 2.5 ADC counts, or 0.016% fs. With this performance, the MAX1464's repeatability is better than most leading temperature sensors in the market.

The MAX1464 has very low ratiometric error as well. Based on the data presented in Table 1, **Figure 1** shows that the largest ratiometric error is 0.64% fs and it happens at V_{DD} = 4.5V and T = +125°C. This error will account for only 0.0064% of the error for a product with a 1% overall error rate (0.64% x 1% = 0.0064%).

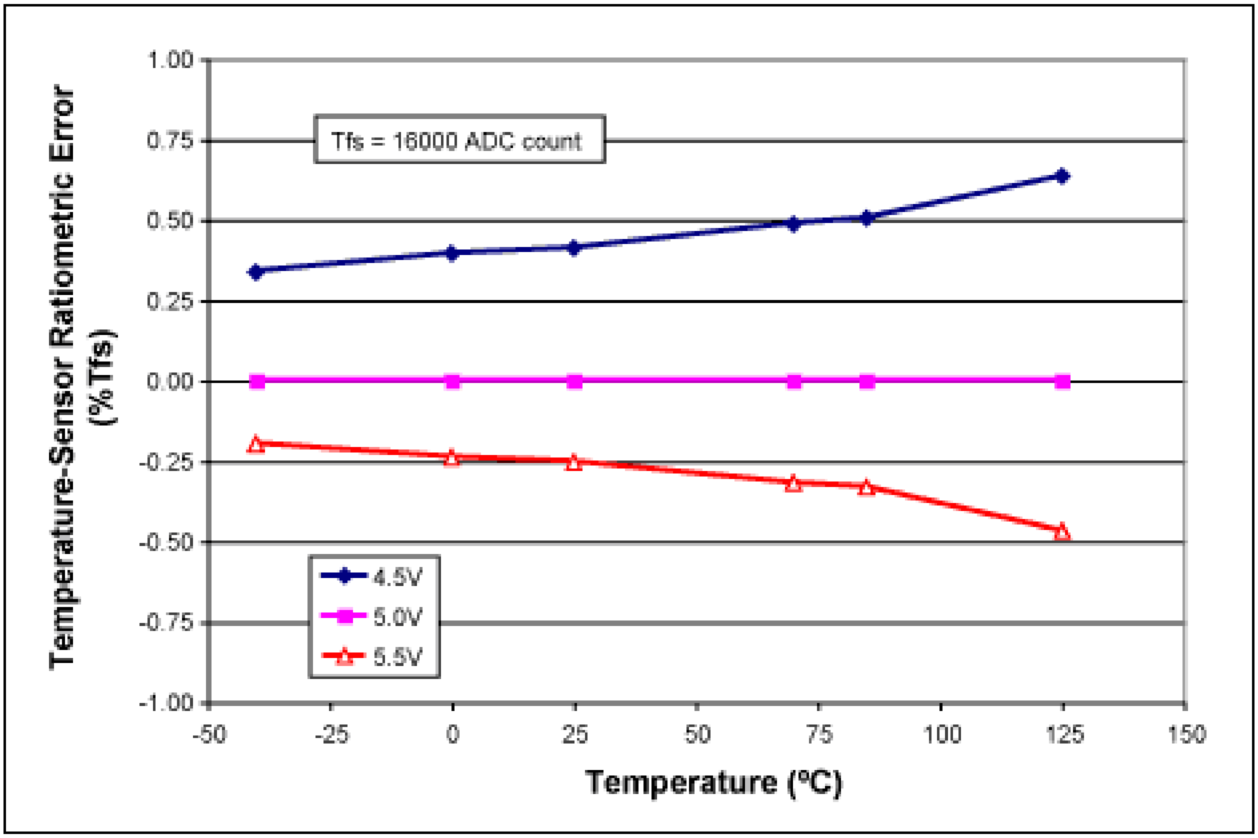

Figure 1. Typical MAX1464 temperature-sensor ratiometric error as a function of temperature and supply voltage.

Even though small, the ratiometric error can be corrected to improve performance.

The error curve in Figure 1 illustrates that errors at +70°C occur at midrange of the ratiometric error curve for V_{DD} at both 4.5V and 5.5V. By simply shifting the error curve around midpoint (+70°C), the effective error is significantly reduced.

Equation 1 is the ratiometric error function at +70°C.

(Eq 1) **ADC_T_error(Vdd, 70C) = 0.088111 x Vdd^2 - 0.14959 x V_{DD} + 0.061092**

Subtracting this error function from every ADC_T reading eliminates the error at +70°C and centers the error curve around the 0% line. **Figure 2** plots the results when we applied Equation 1 to the readings in Table 1. This simple correction reduced the already small internal temperature-sensor ratiometric error by 75%, that is from

0.64% to 0.15%.

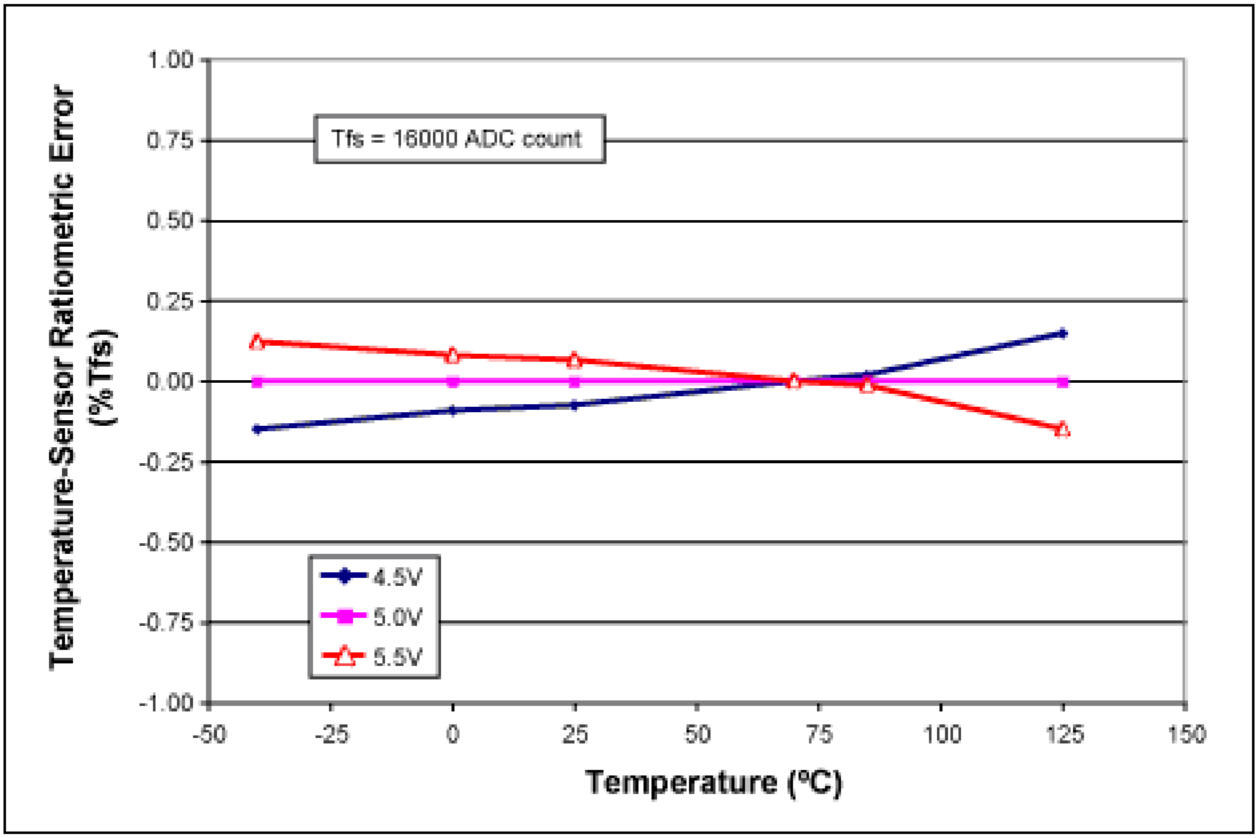

Figure 2. Typical temperature-sensor ratiometric error for the MAX1464 after a one-temperature-point correction is applied.

For some applications where better ratiometric performance is required, the temperature sensor must be characterized at multiple temperature points and Equation 1 must be expanded to be a function of temperature as well. It is important to note here that ratiometric error is typically a function of the design and process; all devices of same type typically have a similar shape and magnitude. One can, therefore, define a function that describes the ratiometric error for a representative group of samples and apply that function to the entire product line. Whether a one-temperature-point or multitemperature-point correction is required, the calculation needs to be performed only once during the product development phase. The resulting formula is then integrated into the compensation algorithm.

Since Equation 1 was driven from actual data, it can be used as starting point and be modified/expanded as necessary. By implementing the multitemperature compensation, the ratiometric error can be reduced to approach the Test System/MAX1464/Sensor repeatability.

The MAX1464 as a Thermometer

The on-chip temperature sensor was designed for use in sensor compensation only. However, if the MAX1464's temperature sensor is characterized, it can be used as a thermometer to monitor absolute device temperature. While ratiometric error is characterized only once for similar devices, each device must be individually characterized for reading an absolute temperature. This is because components of input signal to the ADC_T (temperature-sensor offset, temperature-sensor sensitivity, and CO DAC output) differ significantly among devices.

Temperature-sensor accuracy can be influenced by the level of characterization that one performs. In general, by characterizing the temperature sensor at multiple temperatures and by applying the characteristic function on the ADC_T readings, one can attain extremely accurate readings that surpass most leading temperature sensors in the market. Typically, ±2°C accuracy can be achieved by characterizing the temperature sensor at only two temperature points (**Figure 3**). The process adds only a few milliseconds to the overall compensation process and a few microseconds to the MAX1464's signal-loopduring operation, when it applies the temperature-sensor correction on each ADC_T reading.

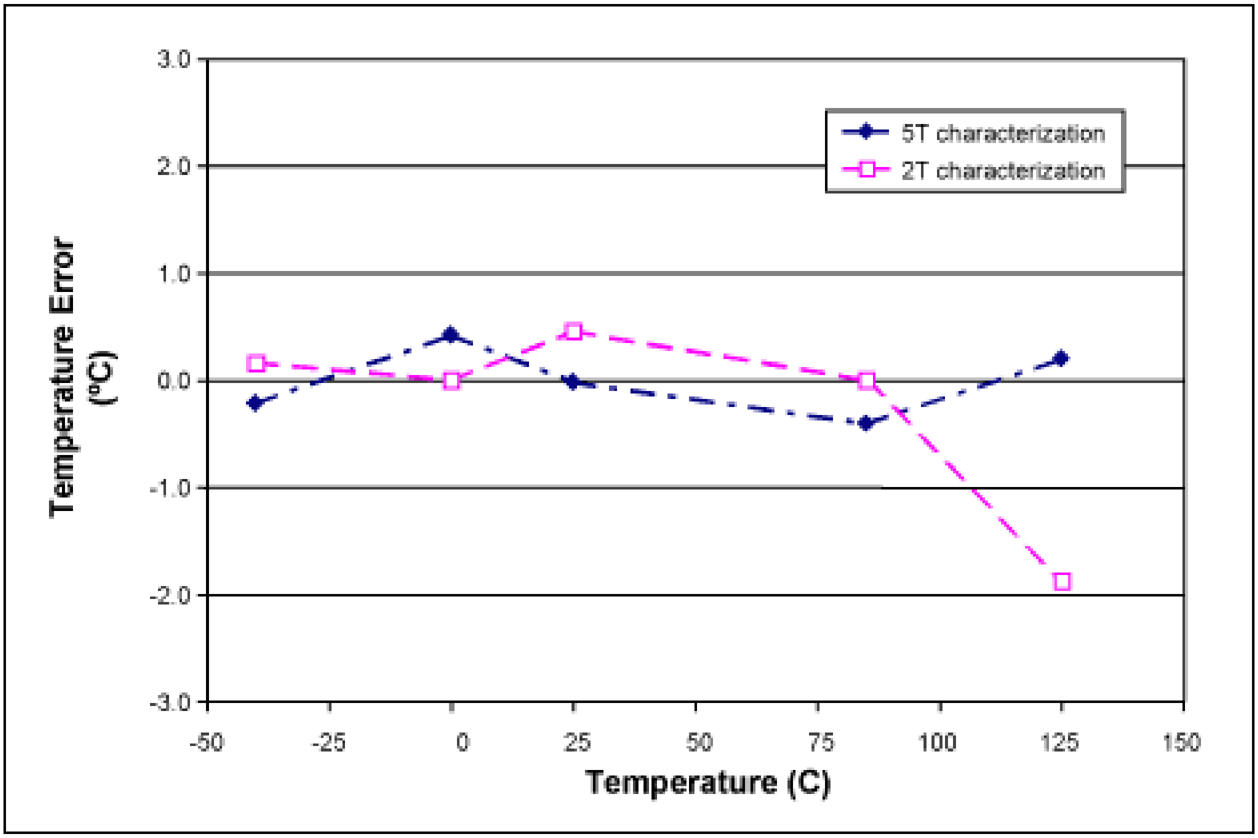

Figure 3. MAX1464 temperature error after correction is applied to the ADC_T readings (PGAT[4:0]=00001; COT [3:0]=1101).

Because the MAX1464's architecture combines the output of the temperature sensor and output of the coarse-offset DAC to generate input to the ADC_T, temperature accuracy is not possible without characterizing each temperature sensor. Needless to say, no temperature-sensor characterization or correction is needed when using the temperature sensor for normal sensor signal compensation.

References

1. MAX1464 data sheet.
2. An application note, MAX1464 Signal-Conditioner, Sensor Compensation Algorithm.

Application Note 3650: www.maxim-ic.com/an3650

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