Optimizing Remote Diode Temperature Sensor Design

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ABSTRACT

Many high-performance systems rely on accurate temperature measurements to optimize performance and ensure reliable operation. The temperature readings can be used to adjust temperature-sensitive elements, such as A/D converters and high-end displays, or the readings may be used to monitor system health and prevent overheating. While modern processors have built-in temperature measurement, these are generally not as accurate as an external temperature sensor and overall system performance may suffer if an external sensor is not used. As system density increases, the use of external sensors that measure many temperature points also help simplify the system management design.

This application note discusses the design considerations for successfully sensing the temperature of a highly integrated system using a remote diode temperature sensor. The application report specifically focuses on the TMP468, but the information can be applied to other remote diode temperature sensors such as the TMP411, TMP451 and TMP461, to name a few. Remote diode temperature sensors sense the junction temperature of a remote PN junction of a bipolar junction transistor (BJT). The BJT can be an integrated transistor in a MCU, GPU, ASIC, FPGA, or a stand-alone transistor such as the common 2N3904 NPN transistor. The use of remote temperature sensors is common in telecom equipment (switches and routers), servers, automotive infotainment, and high-end displays. System design can be quite challenging in highly integrated systems because noise and BJT process variations can cause errors. This application note gives an overview of thermal diode temperature sensors, discusses error sources, and shows how to mitigate system impact of sensor errors. Layout considerations are also discussed.

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1 System Description

Figure 1 shows a circuit diagram of a remote temperature sensing system. The circuit includes the TMP468 device that monitors nine temperature zones using the internal (local) temperature sensor, and eight remote thermal diodes with the associated filter circuitry (R_{S1}, R_{S2}, and C_{DIFF}). Shown in the diagram is a two-wire I^2C or SMBus compatible system management controller that reports the zone temperatures from the TMP468 to a console, or coordinates system cooling and protection. Figure 1 shows overtemperature shutdown circuitry that takes direct hardware action to shut down the system based on the $\overline{\text{THERM}}$ outputs of the TMP468. The TMP468 includes two limits for each temperature zone that are associated with the $\overline{\text{THERM}}$ and $\overline{\text{THERM2}}$ outputs. These limits digitally compare to the current temperature readings and activate the $\overline{\text{THERM}}$ and $\overline{\text{THERM2}}$ outputs.

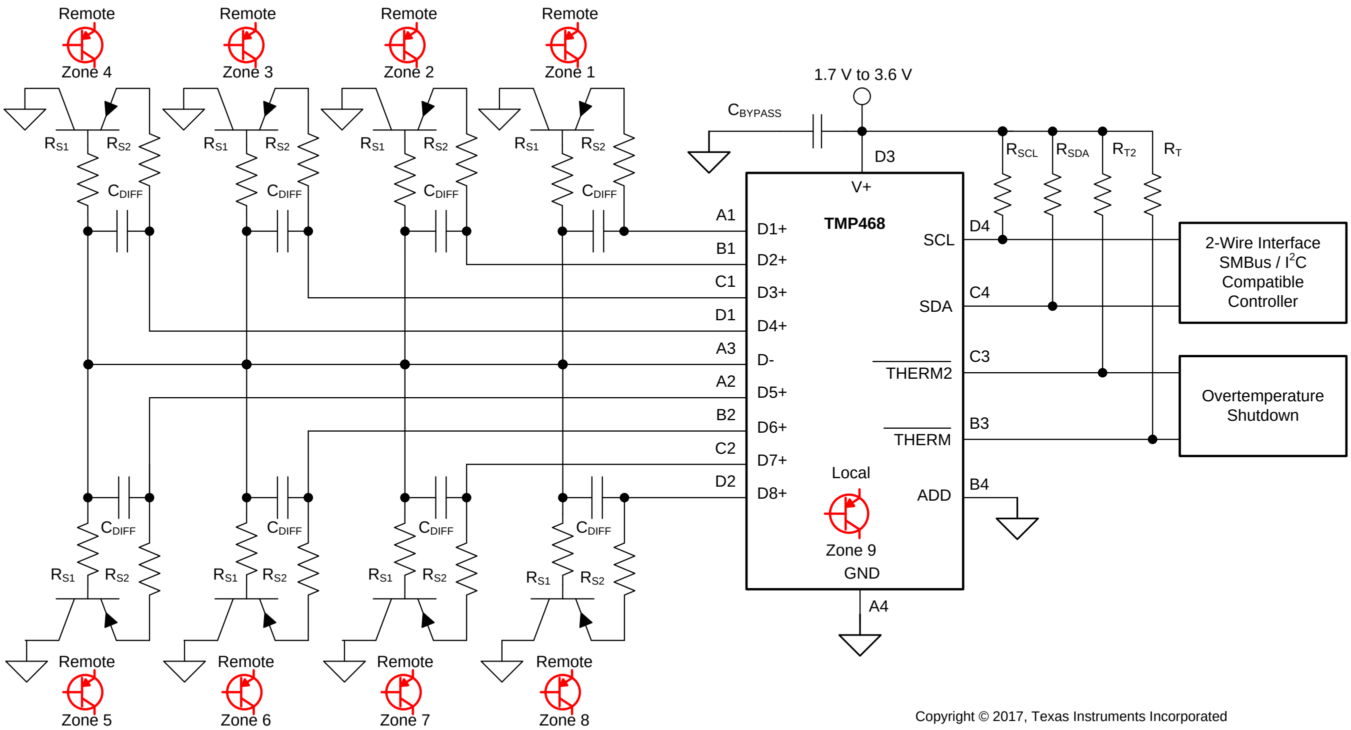


Figure 1. TMP468 System Diagram

1.1 Thermal Diode Overview

The base emitter junction of a BJT has a very predictable transfer function that is dependent on temperature. Remote-junction temperature sensors use this principle to measure the temperature of an external transistor. There are four possible BJT configurations, as shown in Figure 2. The selected configuration is typically dependent on availability and the type of task. In most cases, remote junction temperature sensors measure the junction temperature of another device, such as a high-power processor, FPGA, or ASIC. The most common bipolar transistor found in CMOS processes is a substrate PNP with a collector that is tied to ground or substrate. To measure the case temperature of a device or board temperature, use a discrete transistor, as shown in Figure 2. Complicated systems require robust thermal management solutions with several temperature zones for protection and prevention of thermal runaway. Thus, the TMP468 measures the junction temperature of multiple highly integrated devices, and the temperature of stand-alone transistor junctions placed throughout the system to generate a thorough temperature profile.

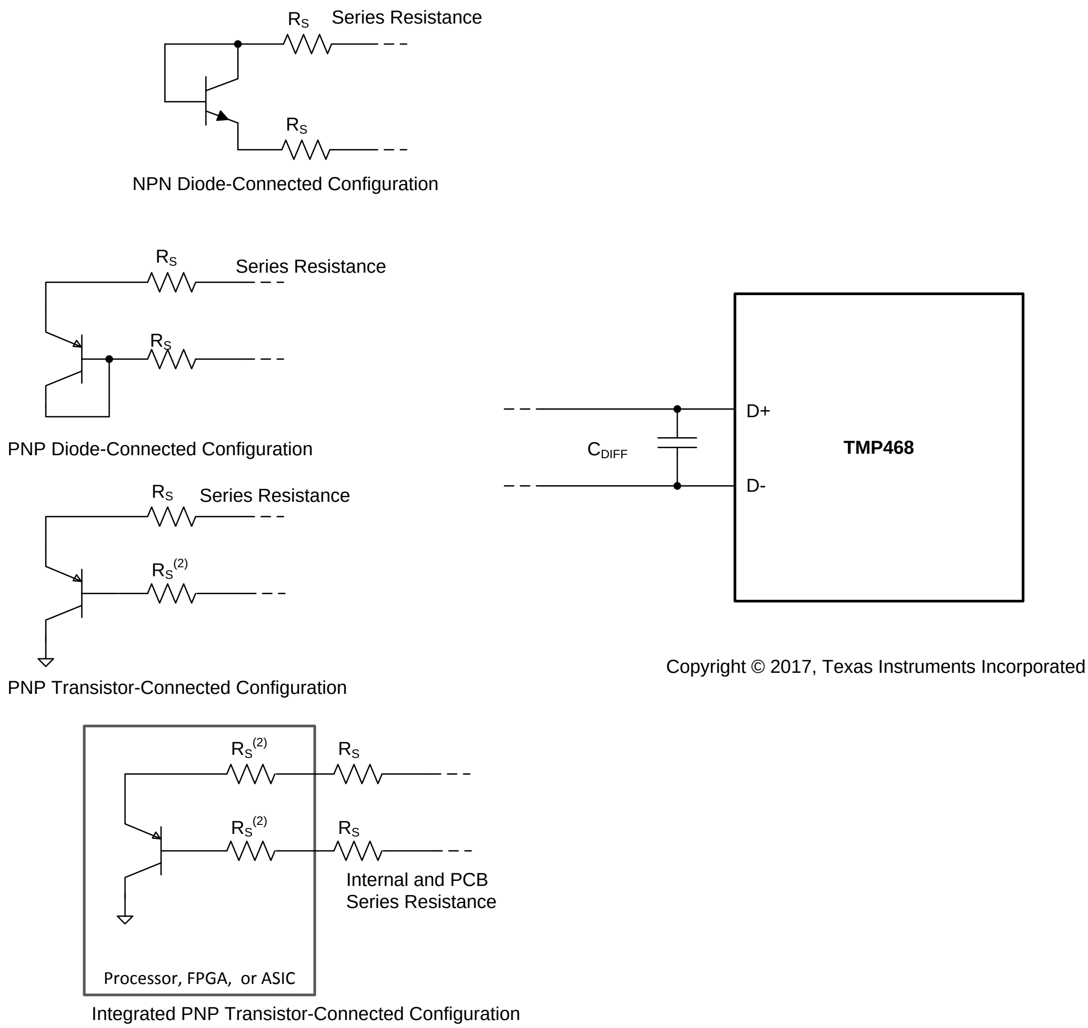


Figure 2. Possible Remote Diodes

Figure 3 shows the most straightforward method of measuring a transistor base emitter voltage by forward biasing the transistor junction with a fixed current.

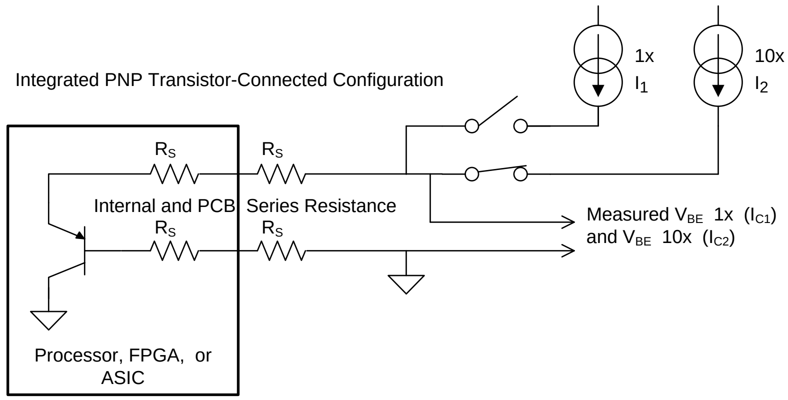


Figure 3. V_{BE} Measurement

The standard Ebers-Moll model equation describes the function of this circuit. The simplified equation for the collector current is shown in Equation 1. Equation 1 has a V_{BE} term.

$$I_C = I_S e^{\frac{qV_{BE}}{\eta kT}}$$

where:
- I_C is the transistor collector current
- I_S is the transistor reverse saturation current
- q is the charge of an electron (1.60217662 ×10^{-19} coulombs
- k is Boltzmann's constant (1.3806485 × 10^{-23} m^2 kg s^{-2} K^{-1})
- η is the ideality factor of the transistor (n-factor)
- T is the temperature of the transistor in degrees Kelvin
- V_{BE} is the base emitter voltage drop (1)

Solving for V_{BE} results in Equation 2:

$$V_{BE} = \frac{\eta kT}{q} \ln\left(\frac{I_C}{I_S}\right) \tag{2}$$

N-factor and the reverse saturation current terms have process dependencies, and can vary widely from one transistor type to another. The device manufacturer can control the collector current, but precision can become costly. This method is not widely used, since error variability in the range of ±9°C has been observed. For these reasons, the two current method approach (as shown in Figure 4) has gained popularity.

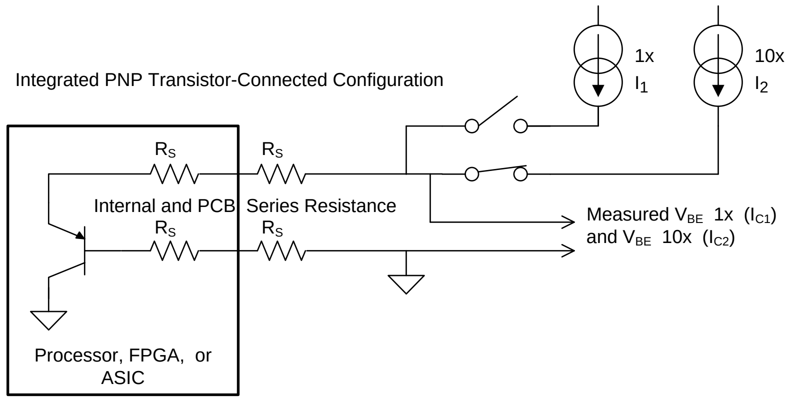


Figure 4. Δ_{VBE} Measurement With Two Currents

The two current method takes the advantage that device manufacturers easily design cost-effective circuitries that provide very precise current ratio, which cancel out the effects of the reverse saturation current. In the two current method, the difference of two voltage measurements determine the temperature, as shown in Equation 3:

$$\Delta V_{BE} = V_{BE1} - V_{BE2} \tag{3}$$

Substituting Equation 2 into Equation 3 results in Equation 4:

$$\Delta V_{BE} = \frac{\eta kT}{q} \ln\left(\frac{I_{C1}}{I_S}\right) - \frac{\eta kT}{q} \ln\left(\frac{I_{C2}}{I_S}\right) \tag{4}$$

Simplifying Equation 4 results in Equation 5:

$$\Delta V_{BE} = \frac{\eta kT}{q} \ln(r)$$

where:

- $r = \frac{I_{C1}}{I_{C2}}$ (5)

Common values for the ratio (r) ranges from 10× to 32×, yielding ΔV_{BE} voltages in the range of hundreds of microvolts. Such small signal levels can be sensitive to noise pickup and PC trace or other series resistance. In addition the process dependency of the n-factor can introduce additional errors if not accommodated. Notice that the Ebers-Moll model solution depends the ratio of the collector current, yet most remote diode sensors only control the emitter current. Hence, variation in BJT β with different emitter current levels can cause errors if excessive variation occurs.

1.2 Thermal Diode Error Sources

This section will cover the major sources of errors involved with remote diode temperature sensing, such as n-factor variation, BJT β variation, series resistance, and noise injection. It will also describe how to overcome them.

1.2.1 Variation of N-Factor

Compensating for n-factor differences is simple if the diode manufacturer specifies the n-factor in the respective data sheet. Typically, a special request is required. The TMP468 includes an independent register for each remote input that can be set to a value between 0.950205 and 1.073829. A simple equation provided in the TMP468 data sheet (Equation 6) can be used to determine the actual register value that must be programmed. The equation result is in decimal, and the n-factor register format is in two's complement with a range of –128 to +127.

$$N_{ADJUST} = \left(\frac{1.008 \times 2088}{\eta_{EFF}} \right) - 2088$$

where

- N_{ADJUST} is the decimal value required by the n-factor adjust register
- η_{EFF} is the n-factor required by the BJT target (6)

To calculate the n-factor setting from the TMP468 register decimal value, use Equation 7:

$$\eta_{EFF} = \left(\frac{1.008 \times 2088}{2008 + N_{ADJUST}} \right) \quad (7)$$

Some remote diode temperature sensors do not include n-factor adjust registers. These devices are typically calibrated for a 2N3904 or an MMBT3904 transistor. An offset register is typically provided in these devices to allow for a one point offset calibration that compensates for errors.

Temperature errors associated with n-factors of different processors or transistor types may be reduced in a specific temperature range of concern through use of software calibration. Typical n-factor specification differences cause a gain variation of the transfer function, so the center of the temperature range must be the target temperature for calibration purposes. Equation 8 can be used to calculate the required temperature correction factor (T_{CF}) to compensate for a target n-factor that differs from the 2N3904 transistor.

$$T_{CF} = \left(\frac{\eta_{SENSOR} - \eta_{PROCESSOR}}{\eta_{SENSOR}} \right) \times \left(T_{CR} + 273K \right)$$

where

- η_{SENSOR} is the n-factor that the remote diode sensor is calibrated for (usually 1.008 or 1.003 for the 2N3904 transistor)
- $\eta_{PROCESSOR}$ is the new n-factor value of the processor or transistor
- T_{CR} is the temperature value at the center of the temperature range (8)

The correction factor must be directly added to the temperature reading that the remote diode sensor produces. For example, when using a remote diode sensor that is calibrated with an n-factor of 1.003 to measure another thermal diode with a typical n-factor of 1.008, for a temperature range of 60°C to 100°C, the correction factor would calculate to:

$$T_{CF} = \left(\frac{1.003 - 1.008}{1.003} \right) \times \left(80 + 273.15 \right) = -1.76°C \quad (9)$$

Therefore, 1.76°C must be subtracted from the remote diode sensor temperature readings to compensate for the differing typical n-factor target.

1.2.2 Compensating for Errors Using Lab Measurements

If a transistor manufacturer does not provide the n-factor, a simple bench evaluation can determine either offset compensation or a viable n-factor setting. Sometimes both are required when tuning for the best performance. Test the target transistor with the default n-factor setting of the remote diode sensor over the temperature range where best accuracy is required. Testing several remote diode sensors (such as the TMP468) and several transistors is recommended as part-to-part variation will be observed. The average of the various readings will be used to determine the proper n-factor and offset. Any variation of the measurements from the average can be used to calculate if the residual error is within system requirements. Create a table of the averaged measured readings (T_M) at each temperature (T_A). Assuming that the temperature error has a linear transfer function, calculate an offset correction term and a new n-factor.

Calculate the slope (m) using the minimum (T_{A1}, T_{M1}) and maximum (T_{A2}, T_{M2}) points using Equation 10:

$$m = \frac{T_{M1} - T_{M2}}{T_{A1} - T_{A2}} \quad (10)$$

A new n-factor can be calculated using m as shown in Equation 11:

$$\eta = m \times \eta_D$$

where

- η_D is the default setting used for the n-factor of the sensor when the measurements are calculated (11)

The offset temperature compensation value is calculated using Equation 10 and the values at the center of the range:

$$T_{OS} = m \times T_{AC} - T_{MC}$$

where

- T_{MC} is the measured output of the temperature sensor at the center of the temperature range
- T_{AC} is the actual temperature center of the range (12)

For example, the TMP468EVM was used to measure the error of the MMBT3904 transistor that is on the board, the corrected n-factor and offset was determined, and the error using the new n-factor and offset was measured. Table 1 lists the measured values and errors on the TMP468 board over a 40°C to 100°C temperature range.

Table 1. Initial Temperature Measurements With N-Factor = 1.008 and Offset = 0

TEMPERATURE (T_A)		DEVICE READING (T_M)		ERROR
40.21°C	313.36 K	38.76°C	311.91 K	–1.45°C
59.98°C	333.13 K	58.45°C	331.60 K	–1.53°C
80.16°C	353.31 K	78.69°C	351.84 K	–1.47°C
99.94°C	373.09 K	98.38°C	371.53 K	–1.57°C

Solving for Equation 10 results in Equation 13:

$$m = \frac{T_{M1} - T_{M2}}{T_{A1} - T_{A2}} = \frac{371.53 - 311.91}{373.09 - 371.53} = 0.998 \quad (13)$$

The new n-factor is calculated using Equation 11 along with the value of m from Equation 13 results in Equation 14:

$$\eta = m \times \eta_D = 0.998 \times 1.008 = 1.0061 \quad (14)$$

Calculate the offset temperature compensation value using Equation 13 and the values at the center of the range (80.16°C in this example of Equation 15):

$$T_{OS} = m \times T_{AC} - T_{MC} = 0.998 \times 353.31 - 351.84 = 0.77 \quad (15)$$

The errors with the default n-factor of 1.008 and offset of 0°C is compared to the error that was measured with the new n-factor of 1.0062 and offset of 0.77°C. The results (listed in Table 2) are plotted in the curve shown in Figure 5. The yellow line shows the results of the TMP468 default settings, and the red line shows the results of the new n-factor and offset. Table 2 and Figure 5 (shown by the green line) also show the effect of an incorrect n-factor value of 1.032, which results in a slope error.

Table 2. Temperature Error Comparison Using Different N-factors and Offsets for MMBT3904 Transistor on TMP468EVM

TARGET TEMPERATURE	MEASURED AVERAGE ERROR		
	N-FACTOR = 1.032 OFFSET = 0	N-FACTOR = 1.008 OFFSET = 0	N-FACTOR = 1.0067 OFFSET = 0.75
40.00°C	–8.14°C	–1.43°C	–0.08°C
60.00°C	–8.65°C	–1.53°C	–0.10°C
80.00°C	–8.93°C	–1.48°C	–0.09°C
100.00°C	–9.53°C	–1.54°C	–0.07°C

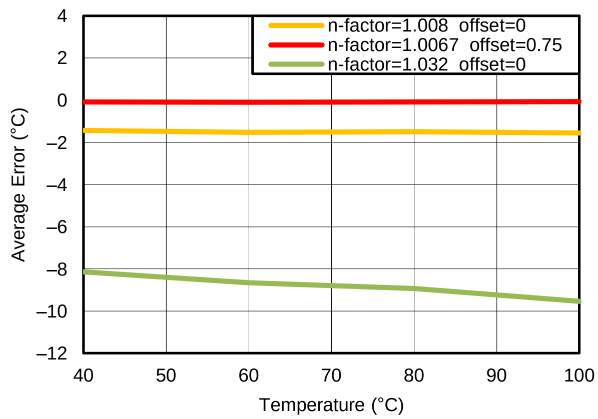


Figure 5. Temperature Error Using Different N-Factors and Offsets for MMBT3904 Transistor on the TMP468EVM

1.2.3 Variation of BJT β

Maintaining an accurate current ratio is very critical since the current ratio directly effects the temperature reading. Errors in the current ratio appear as a temperature error. Equation 5 is dependent on the collector current. In the case of an integrated PNP diode where the collector is tied to ground (as shown Figure 6) the remote sensor forces the emitter current of the transistor.

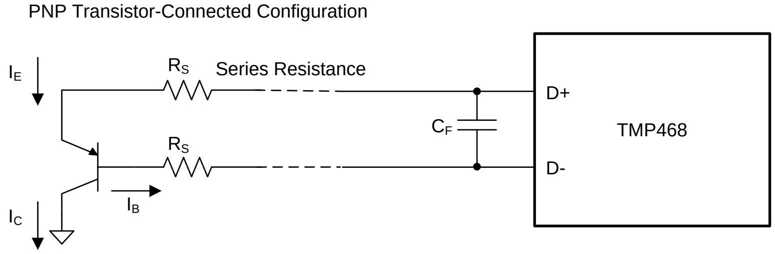


Figure 6. Transistor-Connected PNP Grounded Collector

There is a direct relationship between the emitter current and the collector current as shown in Equation 16. If β varies with the level of the forced emitter current, the collector current ratio is effected. Since the reciprocal of beta plus 1 effects the ratio (see Equation 17) large betas cause a negligible error. When beta approaches one, the change in beta with different currents has a greater effect on the ratio.

$$I_E = I_C + \frac{I_C}{\beta} = I_C \times \left(1 + \frac{1}{\beta}\right) \quad (16)$$

$$\frac{I_{E1}}{I_{E2}} = \frac{I_{C1} \times \left(1 + \frac{1}{\beta_1}\right)}{I_{C2} \times \left(1 + \frac{1}{\beta_2}\right)} \quad (17)$$

As processor geometries decreased, the beta of the substrate PNP decreased. Around the 90-nm process geometry node, betas were less than 10. In addition, it was found that there was beta variation at different emitter current levels for some process types. Remote diode sensors that compensate for the beta variation of the BJT have circuitry that senses the return current on the base, and adjusts the emitter current to compensate for any variation in beta. This beta compensation ensures that the collector current ratio remains intact. The accuracy before and after beta compensation is shown in Figure 7 and Figure 8, respectively. As shown, dramatic improvement in accuracy can be achieved with beta compensation.

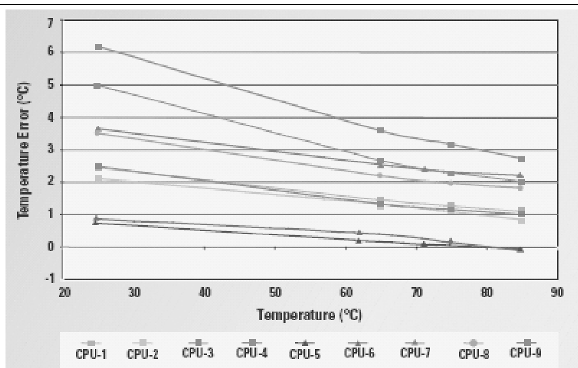


Figure 7. Accuracy Without Beta Variation Compensation

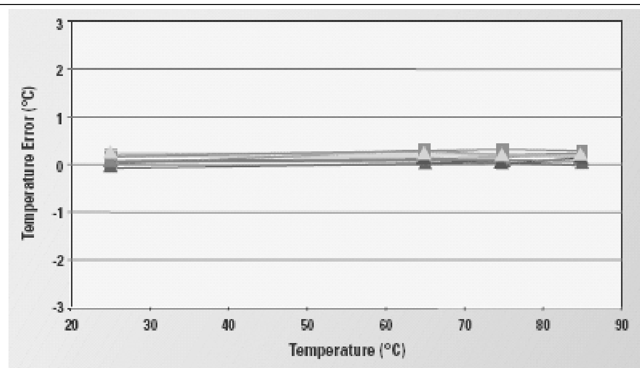


Figure 8. Accuracy With Beta Variation Compensation

Beta variation is simply calculated by measuring the beta of the thermal transistor. Beta is calculated with Equation 18 by forcing different emitter current (I_E) levels and measuring the base current (I_B).

$$\beta = \frac{I_E - I_B}{I_B} \quad (18)$$

Figure 7 shows that beta variation causes offset and slope errors, therefore beta variation can also be compensated by adjusting offset and n-factor values. The method described in Section 1.2.2 can determine the offset and n-factor required for compensation. This method can be used with a remote sensor (such as the TMP468) that does not support beta compensation, but includes offset and n-factor adjust registers.

In addition, BJTs in small geometry SOI processes do not exhibit beta variation. Discrete transistors have very large beta, so even if beta varies, it does not impact the collector current ratio. Some processor manufacturers include an offset compensation value in memory so that software can access this value and program the remote sensor offset adjust register accordingly.

1.2.4 Series Resistance Cancellation

PCB trace resistance can be an issue if it is too high. Most remote diode temperature sensors (such as the TMP468) support series resistance cancellation, but there are limitations. Too high a series resistance can degrade the performance of the remote diode temperature sensor by causing an error in the temperature reading. In addition, series resistance impacts performance by causing a voltage at the remote diode input stage to exceed the design common mode limit.

If another current level measurement is used, three in total, the series resistance term can be canceled out by solving the three equations for V_{BE}. Figure 9 shows the input architecture of the TMP468. The three current levels are 1×, 6×, and 16× (7.5 µA, 45 µA, and 120 µA).

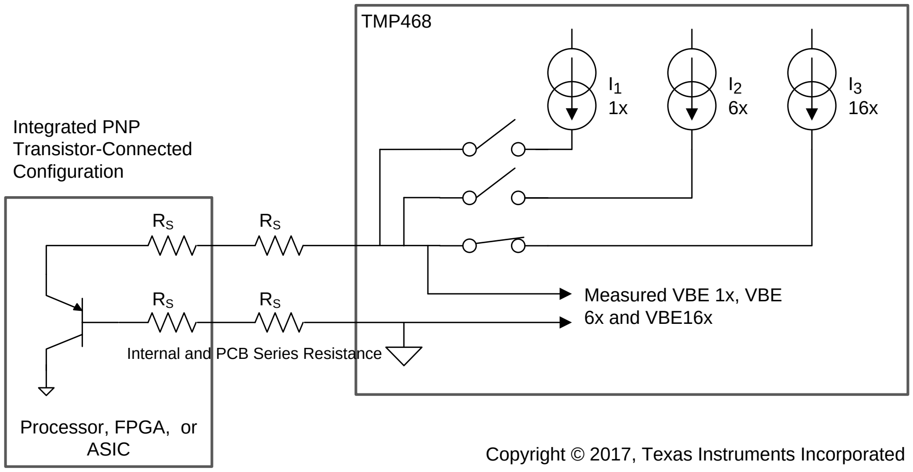


Figure 9. Δ_{VBE} Measurement With Three Currents Cancels Errors Caused by Series Resistance

When the three equations for V_{BE} are solved for R_S, the result is shown in Equation 19.

$$R_S = \frac{\Delta V_{BE2} - K_1 \times \Delta V_{BE1}}{K_2 \times I}$$

where:

- K_1 and K_2 are constants
- I is the 1× current level (19)

Similarly, the equation for T simplifies to Equation 20.

$$T = \frac{K_3 \times \Delta V_{BE1} - K_4 \times \Delta V_{BE2}}{K_5 \times \ln(m1)}$$

where:

- K_3, K_4 and K_5 are constants
- m1 is a current ratio (20)

Figure 10 shows the simplified input stage of the TMP468. The area enclosed by the dashed box is repeated for each D+ input. The D– input is common for all the channels. The current waveform (as shown in Figure 10) cycles through the three levels (1×, 6×, and 16×) multiple times during a conversion. The TMP468 has a ΣΔ ADC architecture that provides good noise immunity. An RC low-pass filter is included that improves the noise immunity.

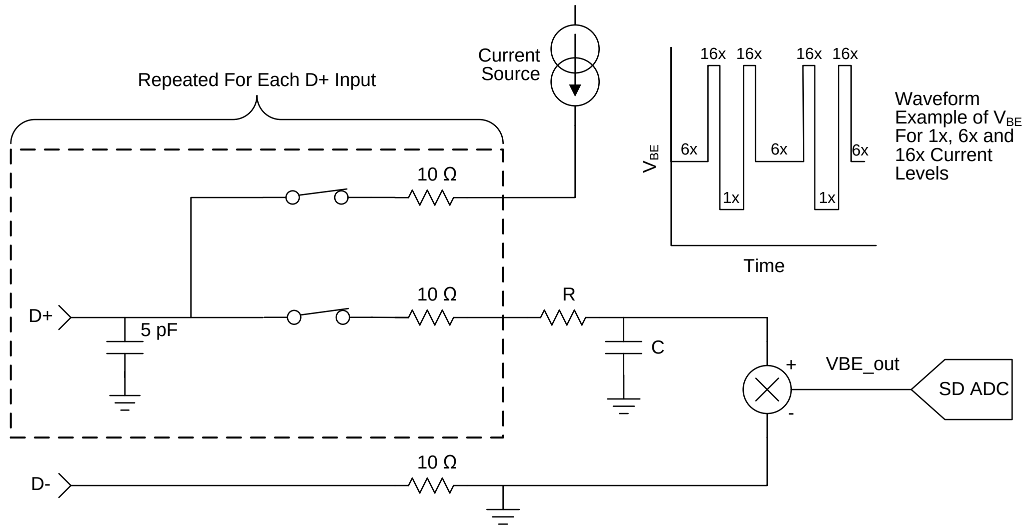


Figure 10. TMP468 Input Stage Simplified Schematic

1.2.5 PCB Leakage Current or Resistance

PCB leakage is another error source that directly impacts the current ratios and causes an error in the temperature reading. Figure 11 shows the actual effect on the temperature reading that is caused by leakage resistance to ground or the power supply voltage. Even the 10-MΩ impedance of an oscilloscope probe can cause several degrees of error. Take care to ensure that the PCB is cleaned properly from fingerprints, flux, and other chemicals that can cause leakage.

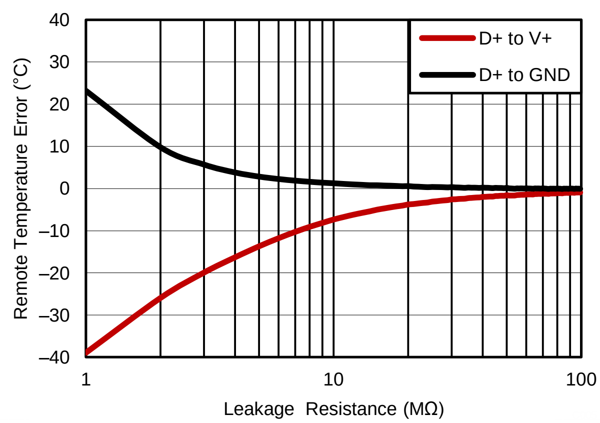
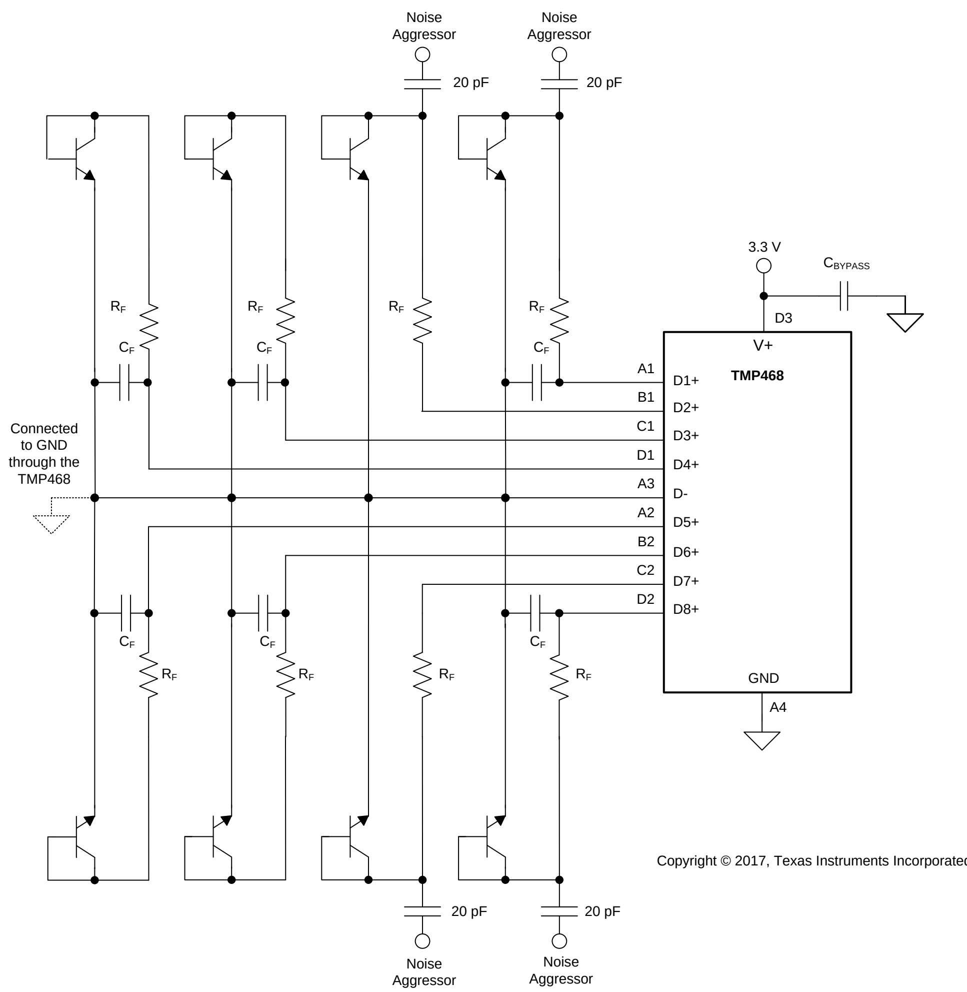


Figure 11. Leakage Resistance Effect on TMP468 Accuracy

1.3 Improving Noise Immunity

Another error source can be caused by EMI or inductive coupling into the remote junction PCB traces. This typically occurs when diode traces run in parallel with high frequency signal lines carrying high currents. Examples of this can be a fast digital clock or placing the thermal diode in close proximity to an inductor of a switching regulator. Without careful PCB layout considerations, the small signal level of the thermal junction voltage Δ_{VBE} of hundreds of microvolts can be swamped by these error sources. Thus, shielding of traces is required. Inductive coupling is also minimized when trace spacing is greater than 10 mils.

The circuit of Figure 12 was used to determine the effect noise has on the performance of the TMP468 remote diode temperature sensor. Comparable effects would be expected with other remote diode sensors. Four channels (D3-D4) were left without any aggressors, but included a filter. The four remaining channels (D1, D2, D7 and D8) included a noise aggressor coupled in through a capacitor. The waveform of the aggressor is shown in Figure 13 and Figure 14 at two different time bases. This noise aggressor is exaggerated over noise that may be residing in a system.



Note all C_F values are 1 nF and all R_F values are 1 kΩ.

Figure 12. Schematic for Noise Tests

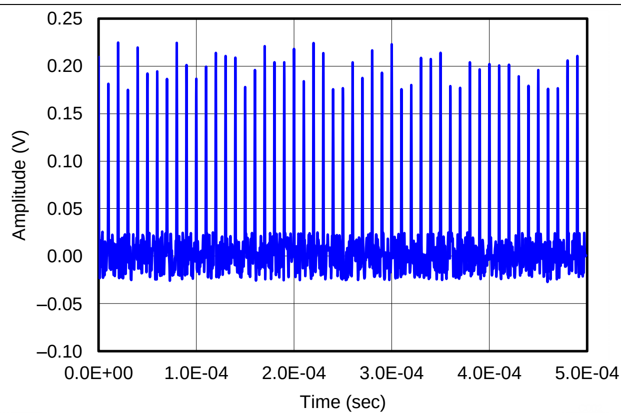


Figure 13. Noise Aggressor Waveform With a 100-μs Time Base

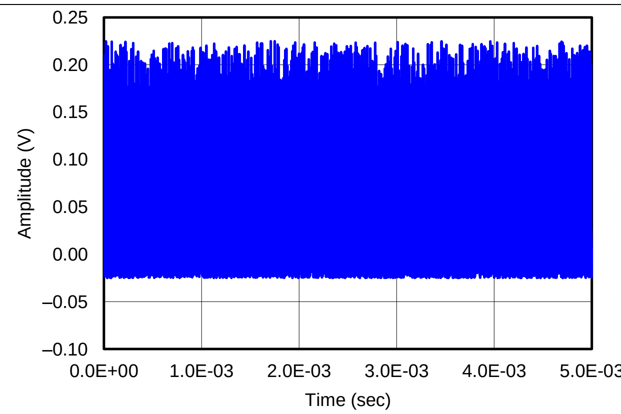


Figure 14. Noise Aggressor Waveform With a 1-ms Time Base

The board residual noise of about 400m°Cp-p can be seen in Figure 15. Notice all channels (including the local temperature overlap) read approximately 21.25°C. The sample rate of the TMP468 was set to once every two seconds. As can be seen, the temperature was very stable for over three minutes. These conditions were also used for the results in Figure 16 where the noise aggressor was injected through 20 pF into channels D1, D2, D7, and D8.

As shown in Figure 16, the channels without the filters (D2 and D7) were impacted severely by the noise aggressor. The channels with the C_F filters (all excluding D2 and D7) were impacted less.

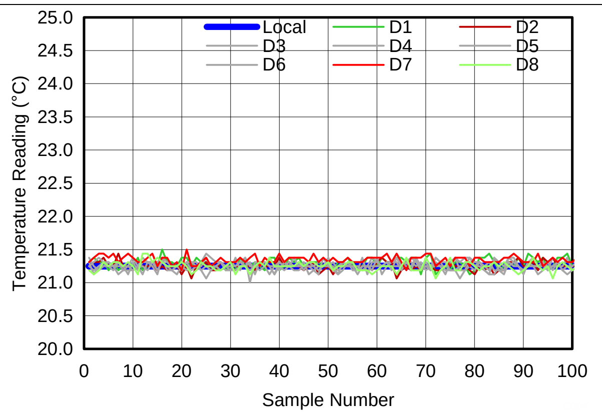


Figure 15. TMP468EVM Baseline Noise Level Measurement Without Noise Injection

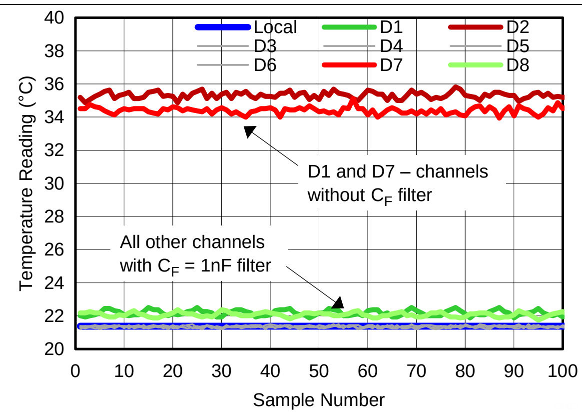


Figure 16. TMP468EVM Noise Level Measurement With Noise Injection

1.4 PCB Layout Considerations

Note in Figure 16 that although channels D2 and D7 have the same filter and noise coupling on the schematic, there is an appreciable difference on the effect of the reading because of different PCB layouts. D2 was run as a single-ended trace without any care as to where the D– trace was placed, as shown in the PCB stack of Figure 17. D7 was run as a true differential pair, as shown in Figure 18.

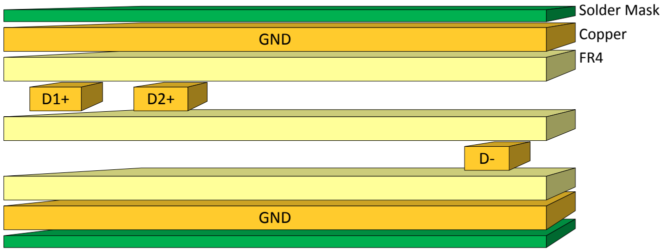


Figure 17. Routing of D+ and D- as Single-Ended Traces on Multiple Layers

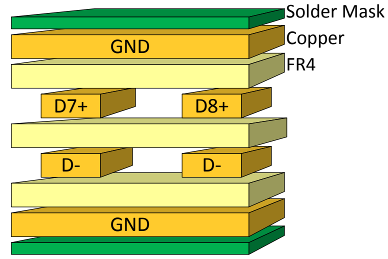


Figure 18. Routing as Differential Pairs on Multiple Layers

The dark red trace in Figure 16 is D2 which used the single-ended layout, while the light red trace shows the response of D7 (the differential pair layout). Figure 16 clearly shows that the differential layout is more effective than the single-ended layout

2 Troubleshooting a Noisy System

This section describes useful techniques for troubleshooting a noisy board. Use a TMP468 evaluation board to determine where the noise is coming from in the system. Cut the traces between the thermal diode and the TMP468 and replace the connection with a cable as shown in Figure 19. This determines if the issue is caused by the actual routing on the PCB. Cut the traces to the on-board TMP468 and patch in the TMP468 on an evaluation board into the system as shown in Figure 20. This determines whether the PCB routing to the sensor is suitable, or the issue is caused by a power supply or other source. The EVM software is simple to use with an evaluation board that connects to a USB port on a PC. Headers are provided on most evaluation boards that simplify EVM patching into a system.

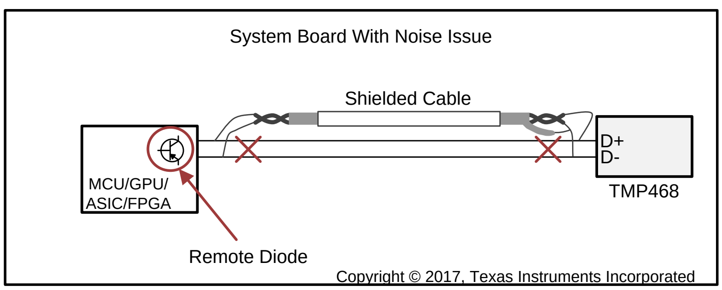


Figure 19. Isolating Noise Coupling Into Thermal Diode Traces

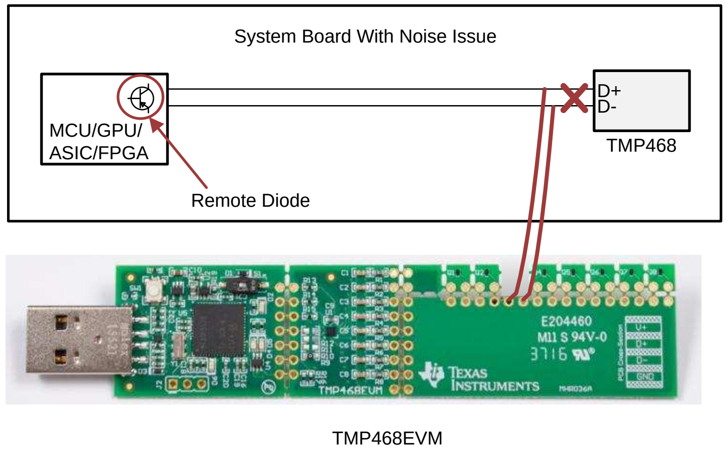


Figure 20. Isolating Noise Coupling Through Power Supply or Other Sources

3 Conclusion

There are many design considerations for successfully sensing temperature of a highly integrated system by using a remote diode temperature sensor. Resistance cancellation helps improve the performance of a remote diode sensor by enabling filtering and eliminating errors that are caused by series resistance. Layout techniques are also important, with the differential pair routing of the D+ and D– lines resulting in the highest performance. N-factor and offset adjust registers help overcome process variations with different BJT manufacturers. All these techniques assist in building a robust system with remote diode temperature sensors.

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

DATE	REVISION	NOTES
January 2017	SBOA173*	Initial release

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