

Accurate Temperature Sensing with an External P-N Junction

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Introduction

Many Linear Technology devices use an external PNP transistor to sense temperature. Common examples are LTC3880, LTC3883 and LTC2974. Accurate temperature sensing depends on proper PNP selection, layout, and device configuration. This application note reviews the theory of temperature sensing and gives practical advice on implementation.

Why should you worry about implementing temperature sensing? Can't you just put the sensor near your inductor and lay out your circuit any way you want? Unfortunately, poor routing can sacrifice temperature measurement performance and compensation. The purpose of this application note is to allow you the opportunity to get it right the first time, so you don't have to change the layout after your board is fabricated.

Why Use Temperature Sensing?

Some Linear Technology devices measure internal and external temperature. Internal temperature is used to protect the device by shutting down operation or locking out features. For example, the LTC3880 family will prevent writing to the NVRAM when the internal temperature is above 130°C.

External temperature compensation is used to compensate for temperature dependent characteristics of external components, typically the DCR of an inductor. The LTC3880 uses inductor temperature to improve accuracy of current measurements. The LTC3883 and LTC2974 also compensate for thermal resistance between the sensor and inductor, plus the thermal time constant.

This application note will focus on external temperature sensing. Proper up front design and layout will prevent performance problems.

Temperature Sensing Theory

Linear Technology devices use an external bipolar transistor p-n junction to measure temperature. The relationship between forward voltage, current, and temperature is:

$$I_C = I_S \left(e^{\frac{V_{BE}}{nV_T}} - 1 \right)$$

$$V_T = \frac{kT}{q}$$

I_C is the forward current

I_S is the reverse bias saturation current

V_{BE} is the forward voltage

V_T is the thermal voltage

n is the ideality factor

k is Boltzmann's constant

For $V_{BE} \gg V_T$ the -1 can be ignored, and the approximate model of the forward voltage is:

$$V_{BE} \approx n \cdot \frac{kT}{q} \ln \left(\frac{I_C}{I_S} \right)$$

The approximation eliminates the need for an iterative solution to the forward voltage. This equation can be rearranged to give the temperature

$$T = q \cdot \frac{V_{BE}}{nk \cdot \ln \left(\frac{I_C}{I_S} \right)}$$

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Because n , k , and I_S are constants, the simplest way to measure temperature is to force current, measure voltage, and calculate temperature. However, the accuracy will depend on n and I_S , the ideality factor and reverse saturation current. These constants are process dependent and vary from lot to lot.

The diode voltage can be rewritten in delta form:

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{nkT}{q} \ln\left(\frac{I_{C1}}{I_{C2}}\right)$$

Rewriting for temperature:

$$T = \frac{(V_{BE1} - V_{BE2})}{\frac{nk}{q} \ln\left(\frac{I_{C1}}{I_{C2}}\right)}$$

If we set the currents such that:

$$I_{C2} = N \cdot I_{C1}$$

we now have:

$$T = \frac{(V_{BE1} - V_{BE2})}{\frac{nk}{q} \ln\left(\frac{1}{N}\right)}$$

Now the temperature measurement only depends on the ideality factor n .

The ideality factor is relatively stable compared to the saturation current. Conceptually, the delta measurement is far more accurate than the single measurement, because the delta measurement cancels the saturation current and all other non-ideal mechanisms not modeled by the equations.

For both cases, the accuracy of temperature measurement depends on the forcing current accuracy, the voltage measurement accuracy, and relatively noise free signals.

Noise Sources

A typical diode temperature sensor is comprised of a 2N3906, 10 μ F capacitor, current source, and voltage measurement.

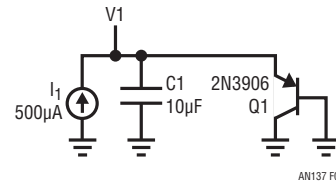


Figure 1.

The operating point at 500 μ A gives a DC impedance of 1.27k Ω . The small signal impedance can be plotted in spice and is 52 Ω out to 10MHz. (Solid line is magnitude of impedance, and dashed line is phase of impedance).

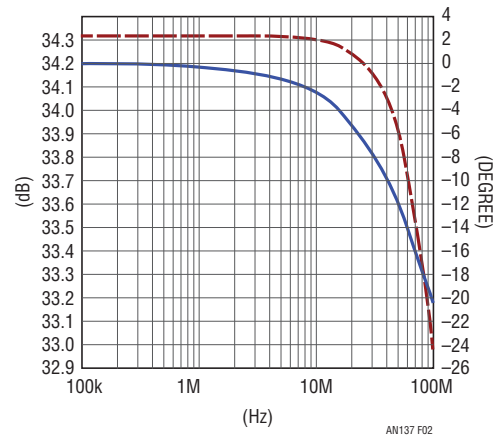


Figure 2.

The small signal impedance can be calculated as follows:

$$R_{\text{small-signal}} = \frac{\left(\frac{kT}{q}\right)}{I_C} = \frac{26\text{mV}}{I_C} = \frac{26\text{mV}}{500\mu\text{A}} = 52\Omega$$

This implies that fast clock and PWM signals may inject noise into the measurement if the driving impedance is close to 52 Ω .

A simulation of a capacitive coupled source shows that the filter capacitor is quite effective.

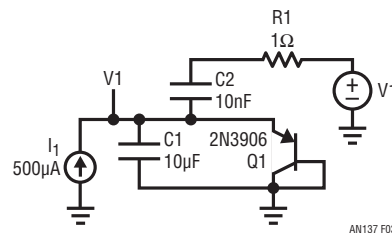


Figure 3. Pulse (0 3.30 10ps 10ps 100ns 2.5µs 10000)

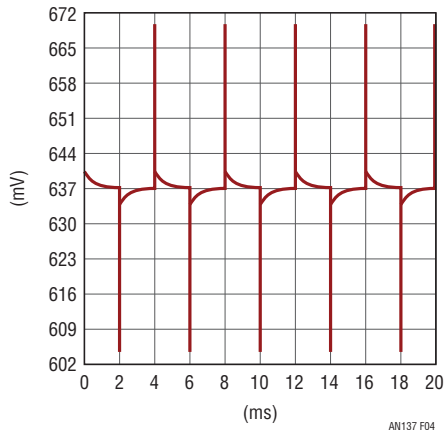


Figure 4.

The simulation uses a 10ps 3.3V signal (V1) injected into the p-n junction (V1) via a 10nF capacitor (C1). Even a 10nF coupled noise source with very fast 10ps edges can only generate 30mV spikes shown in the simulation plot. Another source of error comes from ground impedances.

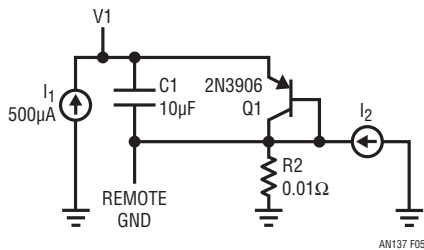


Figure 5. Pulse (0 2A 0 10n 10n 100ns 2.5µs 10000)

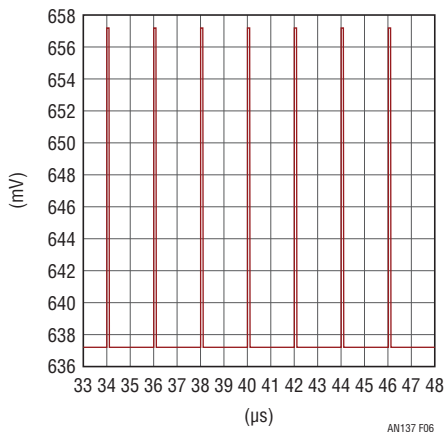


Figure 6.

A 2A current and 10mΩ trace results in a 20mV error. A typical ΔV_D is

$$\Delta V_{BE} = \frac{nkT}{q} \ln\left(\frac{1}{10}\right) \approx 60\text{mV}$$

For a 10% duty cycle, this might result in a 2mV DC shift. A third source of error is a magnetic field and loop. Magnetic coupling can be modeled as a coupling between inductors.

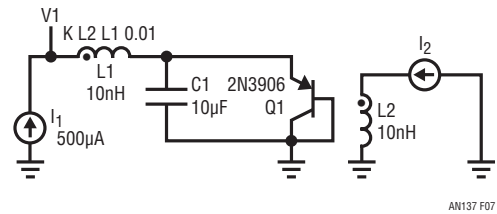


Figure 7. Pulse (0.2A 0 10n 10n 1.25µs 2.5µs 10000)

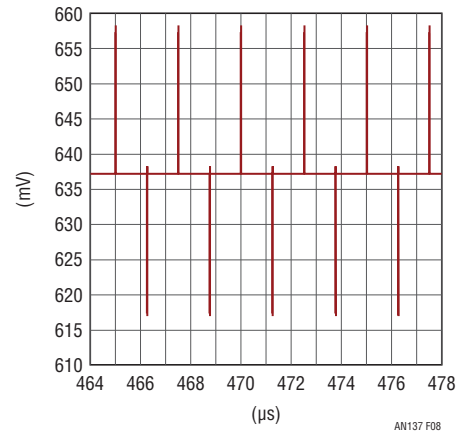


Figure 8.

A 3cm PCB trace over a ground plane can have about 10nH of inductance. If 2A is injected into a parallel trace and the coupling is 1.0%, 30mV of noise can be generated, possibly causing a DC shift of 3mV.

HOW NOISE AFFECTS MEASUREMENTS

Linear Technology devices typically implement a lowpass filter, which filters spikes and noise. However, in some cases filtering results in a significant DC shift.

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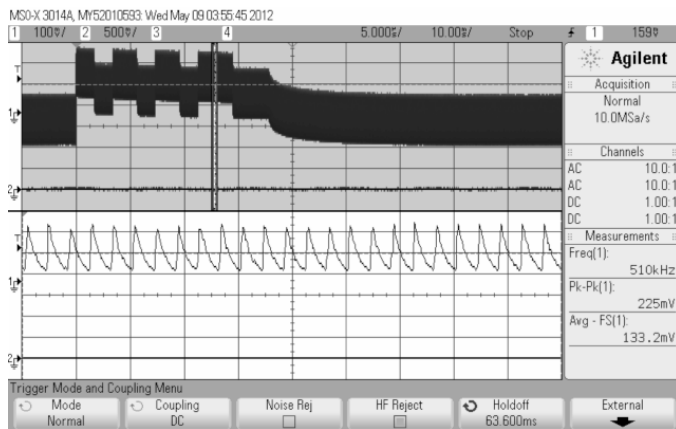


Figure 9.

The example shown in Figure 9, from an LTC3880, shows an asymmetrical waveform on the TSENSE pin (channel 1) caused by injecting some of the switch node signal into the TSENSE pin. When this is filtered, it results in a DC shift. If temperature is calculated using a ΔV_{BE} calculation, and the DC shift is the same for both V_{BE} measurements, the effect will be cancelled out. This means that if the error mechanism is consistent between current measurements, ΔV_{BE} is robust. If the single V_{BE} measurement is used, the DC shift from the filtering will be a source of measurement error. (LTC3880 does not support single ΔV_{BE} measurements)

If the magnitude of noise is very large with respect to ΔV_{BE} , and the noise is asymmetrical (as in the scope shot) and different between current measurements, ΔV_{BE} cannot cancel out the noise. In this case a single measurement can produce a more accurate temperature measurement. For example, suppose noise causes an error of 50mV. A typical ΔV_{BE} is 70mV. The error can be as high as 70%. If a single V_D is used, the error is about 50mV/600mV, or 8%.

Therefore, in systems with systematic noise, the ΔV_{BE} measurement produces the highest accuracy by eliminating I_S as a source of error. (See ΔV_{BE} equation). In systems with large non-systematic noise, the V_{BE} measurement produces the highest accuracy.

Overall, the best accuracy comes from a good layout that ensures near zero noise that is systematic, and uses a ΔV_{BE} calculation.

Non-systematic noise sources require good layout because the ΔV_{BE} approach cannot reject them.

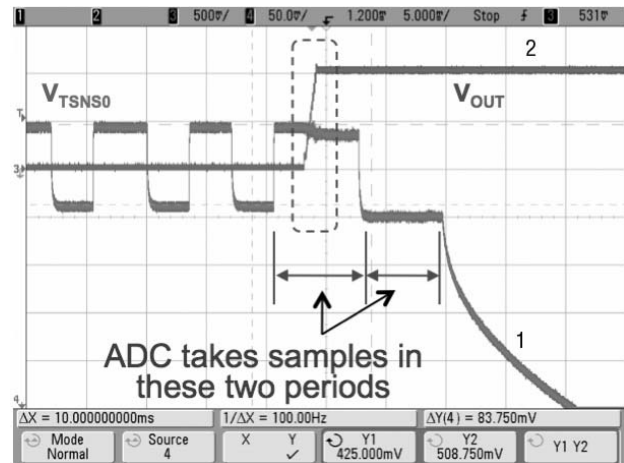


Figure 10.

An Example Coupling Problem

The example shown in Figure 10 comes from an LTC3880. Signal 1 is the TSENSE signal. When the LTC3880 is applying 32µA, you get the higher signal level, and when it is applying 2µA, you get the lower signal level. The last high and low portions of the waveform are where the two measurements are taken. Signal 2 is the V_{OUT} of the LTC3880, which is coupling into the 32µA measurement.

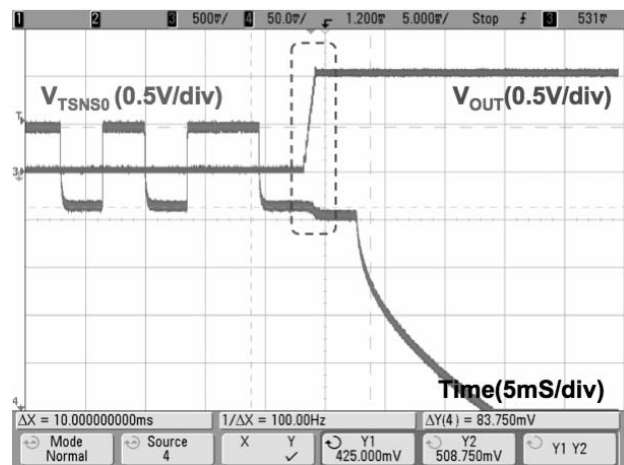


Figure 11.

The same coupling can occur in the 2µA measurement as shown in Figure 11. The asymmetry comes from the fact that the coupling affects only one of two measurements, so it is not cancelled by the ΔV_{BE} calculation. Furthermore, the error will appear random because the output turn-on event and the current forcing mechanism are not synchronized. The only defense against this error is prevention of the coupling by proper layout, or widening the fault limits.

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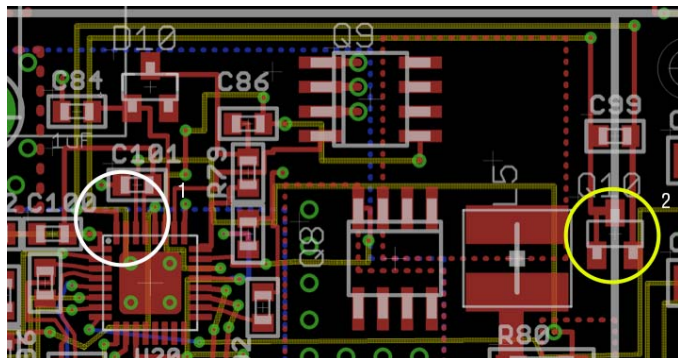


Figure 12.

MITIGATING ERROR SOURCES

There are two primary methods of preventing errors, both require proper PCB layout. The first involves elimination of shared ground paths. The second involves proper signal trace routing.

Linear Technology data sheets specify how to return current from the collector and base of the temperature measurement transistor to the device. Typically the current returns to a sense ground (SGND), or an amplifier negative (–) input.

The current should return to the device via its own sense trace to ensure there is no shared impedance with high current paths, and to the data sheet specified pin.

Figure 12 shows a LTC3883 and 2N3906 PNP current sense. Q10 in circle 1 is the p-n junction temperature sensor and is filtered by C99. The purpose of C99 is to provide a low AC impedance to prevent any DC offsets from rectification or non-linear waveforms, and to keep coupled noise out of the LTC3883 ADC. The routing uses two parallel pairs on the same layer so that any coupling from noise sources becomes a common mode signal to the ADC in the LTC3883 and are rejected. The anode trace routes to the sense pin to the LTC3883 Pin 32 shown in circle 2, and the cathode is routed to SGND: the exposed PAD on the back of the LTC3883. The cathode routing to the exposed PAD ensures no high current from the power ground flows through the sense line.

Figure 13 shows an LTC2991 and two 2N3906 PNP temperature sensors. As in the previous example, capacitor filtering is added near the PNP. However, capacitor filtering was also added at the input of the LTC2991.

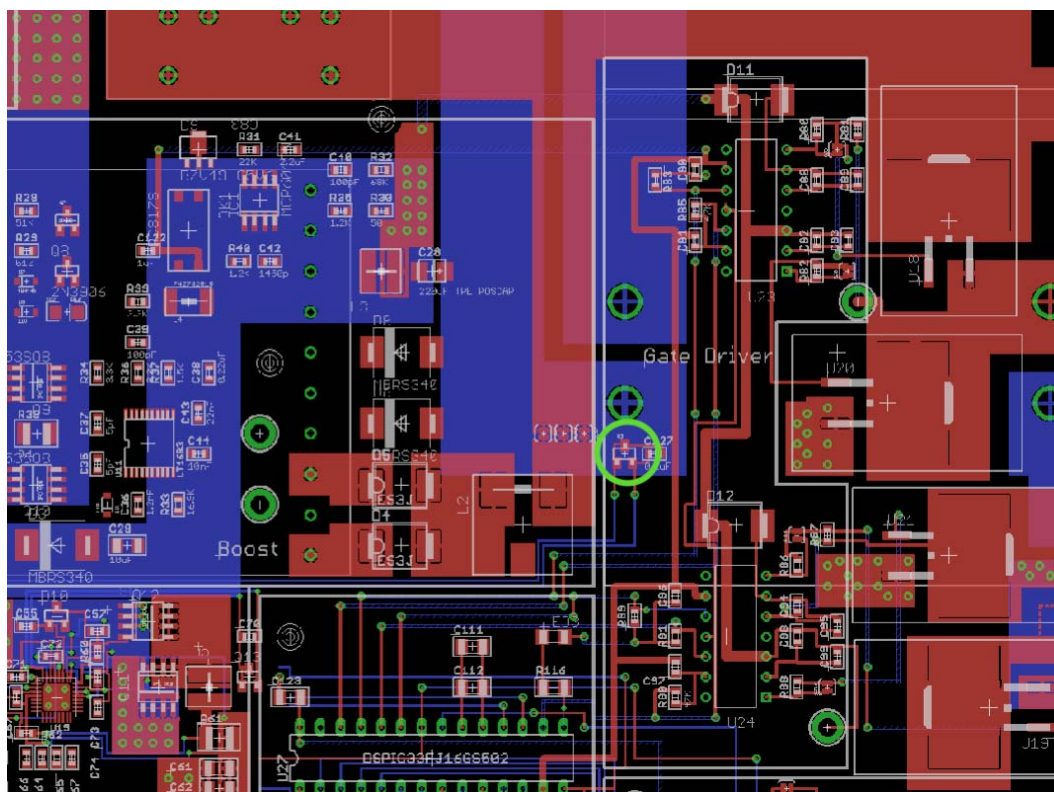


Figure 13.

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The longer trace run offers more opportunity to pick up noise farther from the PNP due to trace inductance. Typically this capacitor is added as an option and installed only if there is a problem. Additionally, notice that the routes avoid switching areas by following the edges of the plane between functional circuits. The routes from the PNP farthest to the right go right between a LTC3883 buck converter below, and a LT1683 isolated boost above.

NOTE: Linear Technology strongly recommends **Placement** of a filter capacitor near the PNP temperature sensor, **Routing** differentially, and **Avoiding** noisy signals. **Long** routes may pick up more noise, so optionally add a filter capacitor near the device.

Some designs may use a power block with built in temperature diode. Some of these power blocks do not have a pin for the low sense of the diode. These blocks may not have a filter capacitor. In these situations, you can place a filter on your board as close to the high side diode sense pin of the power block as possible, and try to minimize all noise sources. A low sense line can still be routed from the power ground, but you can't eliminate the shared current from the switching path, so some noise will be injected. You can mitigate some of the problems that may result by:

1. Using a slower V_{OUT} ramp rate when turning on
2. Adding an offset to the measurement using the proper register (digital power device) to lower the measured temperature
3. Raising the overtemperature fault limit
4. Adding a capacitor on the power block

CHOICE OF P-N JUNCTION DEVICE

Even though a diode can be used to measure temperature, a diode connected PNP or NPN is preferred. The ideality factor of a diode is up to twice as large as a diode connected bipolar transistor. Some diodes do not exhibit increasing ΔV_{BE} with temperature, resulting in large errors

over temperature. In general, a large ideality factor will not produce an accurate temperature measurement using the ΔV_{BE} method. The large ideality factor will lead to larger ΔV_{BE} . Furthermore, V_{BE} may be lower because of differences in I_S . This may use less of the dynamic range of the ADC and increase signal to noise ratio. In the case of a single V_{BE} measurement, this will degrade results more.

NOTE: Use a diode connected bipolar transistor rather than a true diode. If you want to use a diode anyway, contact Linear Technology for advice on suitability for the given device.

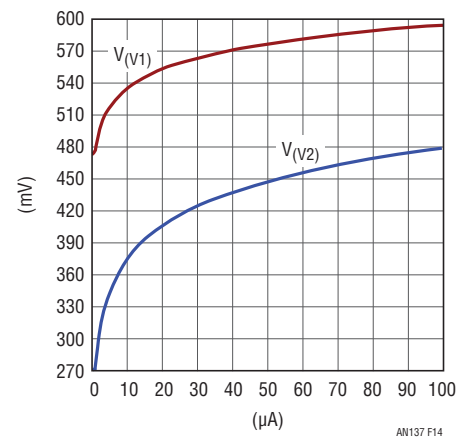


Figure 14. 2N3906 and IN4148

An LTspice® simulation demonstrates the difference between a diode connected 2N3906 and a 1N4148. The diode has almost 150mV lower voltage at 30 μA .

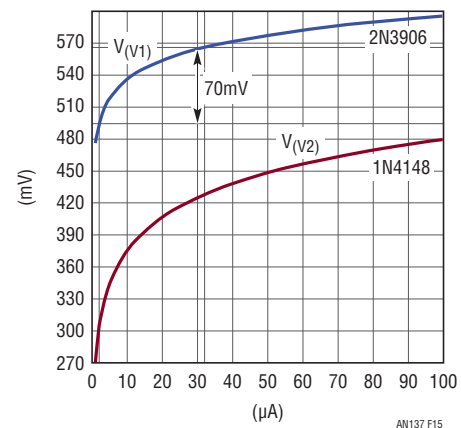


Figure 15. 2N3906 DV_{BE}

The diode-connected transistor shows a typical room temperature ΔV_{BE} of 70mV.

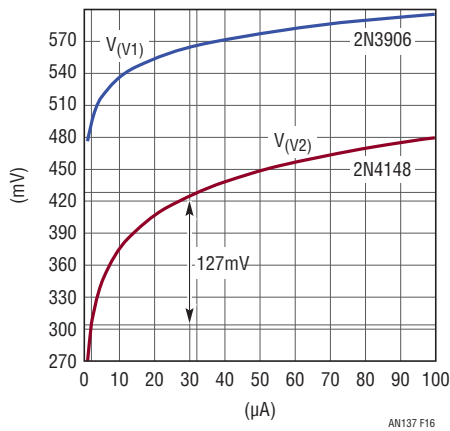


Figure 16. IN4148 ΔV_{BE}

The diode shows a typical room temperature ΔV_{BE} of 127mV. If the part is using a ΔV_{BE} measurement, and if the ADC has a null and diff amp with gain, you must make certain the device can handle the larger ΔV_{BE} .

In all cases, if a diode is used, the controller IC must have a register for setting the ideality. Some Linear Technology controller ICs have a register for this and others don't. The ones that don't are typically set for a 2N3904 or 2N3906.

REVIEW OF DESIGN RULES

A simple set of design rules can prevent a lot of problems:

1. Use a diode-connected transistor. Either 2N3904 or 2N3906. Follow recommendations on the data sheet.
2. Place a filter capacitor near the diode (less than a few millimeters). Add a capacitor near the controller IC if the transistor is more than a couple of inches away if there is space.
3. Route a differential connection from the transistor to the controller IC with minimum spacing whether the part has a separate -TSENSE pin or not. If not, tie the low side to the SGND pin. If there is no SGND pin, use the PGND. Connect at the pin in all cases if possible.

4. Avoid routing near noise generators such as switch nodes, large current traces, large transformers, etc.
5. If using a power block, add a filter cap to the block if possible, or as close as possible to the diode pin if it can't be on the power block.
6. Use a power block with two-pin sensing of the diode if possible.
7. If you have a sub-optimal layout, add offset to the offset register if one is available, or raise the fault limit. In some designs you can make these adjustments during turn on or soft start and restore them during steady state.

APPENDIX A: GENERAL NOISE SOURCES AND MITIGATION

A more general and analytical approach to noise is offered based on material from Noise Reduction Techniques in Electronic Systems, Henry W. Ott. These principles can guide you in solving problems not directly covered in the application note.

Noise Sources

Conduction: noise on any PCB trace will move noise from one part of the PCB to another. Generators of voltage noise are the gate drivers, the switch node, and switching currents that flow through resistors and inductive traces.

Coupling through Impedance: Any time two currents share an impedance, the resulting voltage from one current path is superimposed on the resulting voltage due to the other current path. Shared current paths include the gate-drive-loop/drain-source-loop/temperature-sense-loop.

Coupling through parasitic impedance: PCB traces that are close together can couple through parasitic capacitance and mutual inductance. Low impedance switching nodes can couple to higher impedance sense nodes. For example, a gate drive can couple into a temperature sense line via stray capacitance, or a switch current can couple into a temperature sense line via an inductively coupled parallel trace.

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NOISE MITIGATION

Capacitive Coupling

If a noisy trace is routed next to a sensing trace, the noise will couple to the sensing trace via capacitance.

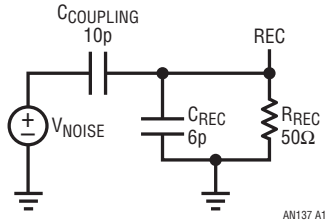


Figure A1.

The analytical expression of the coupling from Ott is:

$$V_{REC} = \frac{j\omega \left[\frac{C_{COUPLING}}{C_{COUPLING} + C_{REC}} \right]}{j\omega + \frac{1}{R_{REC}(C_{COUPLING} + C_{REC})}} V_{NOISE}$$

In the case where R_{REC} is smaller than the impedance of the two capacitors, the equation can be simplified to:

$$V_{REC} = j\omega R_{REC} C_{COUPLING} V_{NOISE}$$

To get a sense of magnitude, a simulation of the above circuit with an input of 5V to represent a gate drive signal, and 50Ω to represent a temperature sensor, the following is the frequency response:

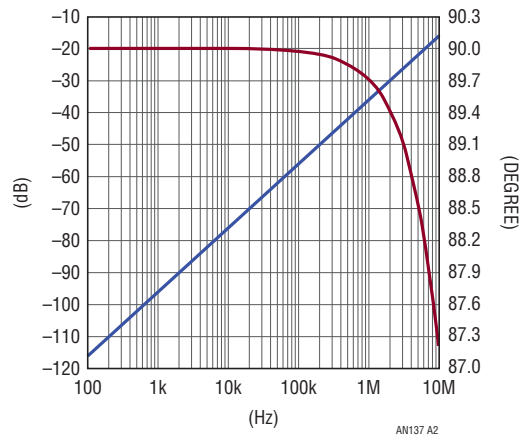


Figure A2.

At 500kHz, the noise coupled to the receiver (temp sensor) is 10mV.

If a shield is added, the equivalent circuit looks like this:

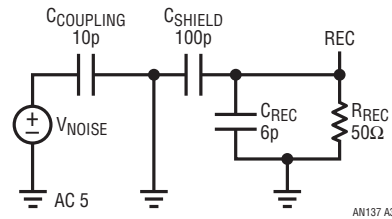


Figure A3.

In this case there is no coupling to the receiver at all. An example of shielding is given in the LTC2991 data sheet as shown in Figure A4:

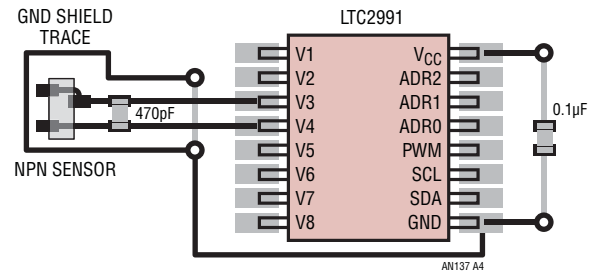


Figure A4.

In this case, the signals are routed differentially, so the shield is protecting against capacitive coupling into both traces. Notice that a portion of the traces is not shielded. This area must be kept small and away from noise sources.

The example uses 10pF coupling to give some general idea of magnitudes of coupling. It is best to make real estimates of coupling capacitance and calculate the effect.

Also note, that parallel routing does not protect against capacitive coupling if the low sense is not a high impedance input.

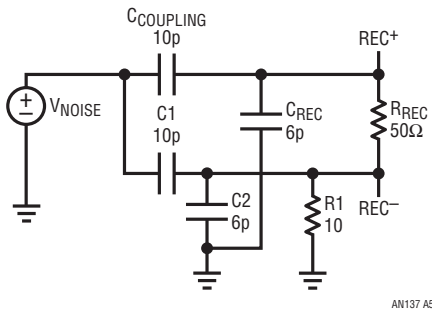


Figure A5.

The model in Figure A5 shows capacitive coupling into both traces.

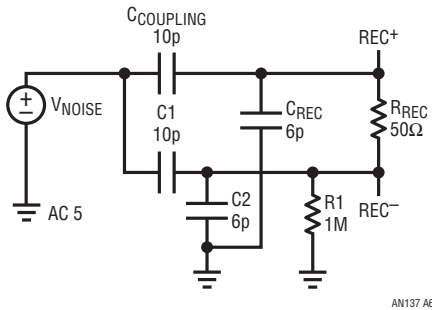


Figure A6.

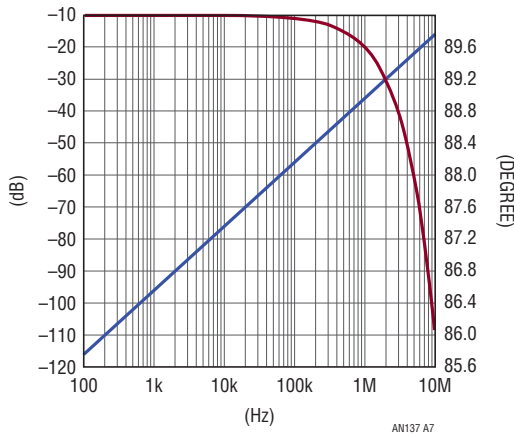


Figure A7.

The frequency response is almost identical to the single route because the impedance of the negative sense is almost zero, therefore the noise can't couple into it to cancel the high side.

If the impedance on the negative sense is very high, such as 1M shown in Figure A6:

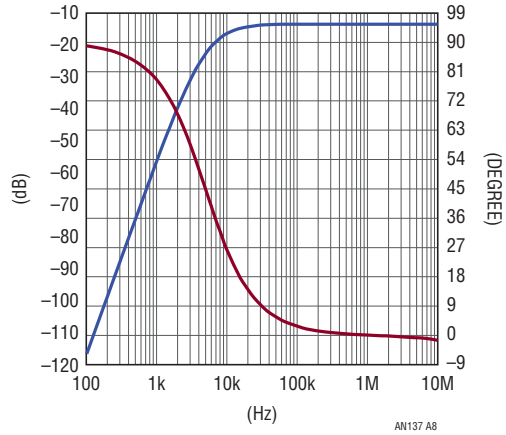


Figure A8.

the attenuation is 80dB at 10kHz.

Therefore, parallel routing would work on an LTC2991 current/temperature monitor, which has ± high impedance inputs, but would not work on an LTC3880 family digital power buck converter which has a low impedance minus input.¹

One last note: looking at the coupling equation:

$$V_{REC} = j\omega R_{REC} C_{COUPLING} V_{NOISE}$$

If R_{REC} is reduced, so is the coupled noise. Adding a capacitor to the input of the receiver will lower the AC impedance. The simulation of this is left to the reader.

Inductive Coupling

Inductive coupling occurs when high currents flow through a trace, creating a magnetic field, and the field enters the current loop of another circuit. The current loop will have a series voltage noise source from the external field.

$$V_{REC} = j\omega MI$$

Note 1: Parallel routing will still eliminate shared current coupling from power ground

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The received noise voltage is proportional to the mutual inductance and current. For example:

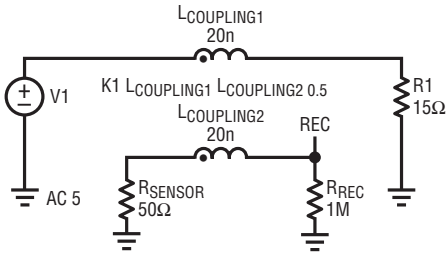


Figure A9.

Suppose the noise source is 5V, like a gate driver, driving 15Ω, which is about 300mA, similar to a typical gate driver. This couples into a 50Ω sensor that drives an amplifier input with 1M input impedance.

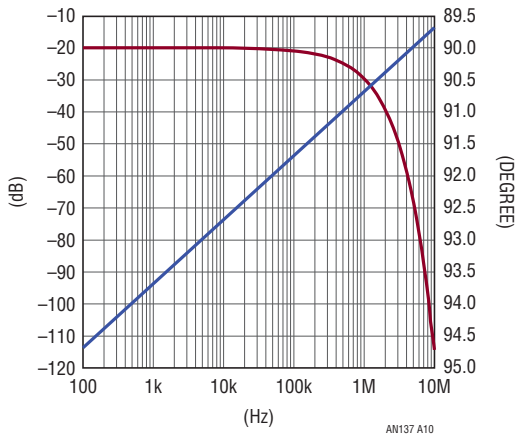


Figure A10.

This will produce about 10mV at the receiver at 500kHz, (shown in Figure A10) a value similar to the capacitive coupling example.

The trace length causes the inductance, but the mutual inductance (represented as coupling factor in the simulation) causes the coupling. The mutual inductance is proportional to the area of the loop with the sensor and receiver.

Suppose the coupling was reduced to 0.05:

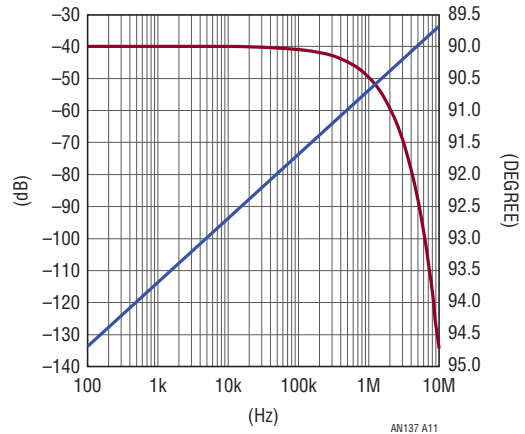


Figure A11.

The result is a 20dB improvement, or 1mV of coupled noise at 500kHz (shown in Figure A11).

There are several ways to make the loop smaller. The high side sense can be routed over a ground plane. This will only help at high frequencies because at low frequencies the current will take the shortest path through the ground plane, which will not be under the trace. Furthermore, the shared ground may cause coupling, which is discussed in the next section.

The high side and low side of the sensor can be routed as parallel traces as close together as possible. As long as the current only flows through the low side sense and not an alternate ground path, this will make the loop area very small. If there is an alternate ground path, the current will only flow through the low sense line if the frequency is high. Most situations allow this routing except some power blocks discussed in the main portion of the application note.

Also, a shield may be added around the parallel traces. Shields may be grounded at either end, so this must be considered. Ott gave experimental data that will aid intuition in deciding how to ground the low sense and shield.

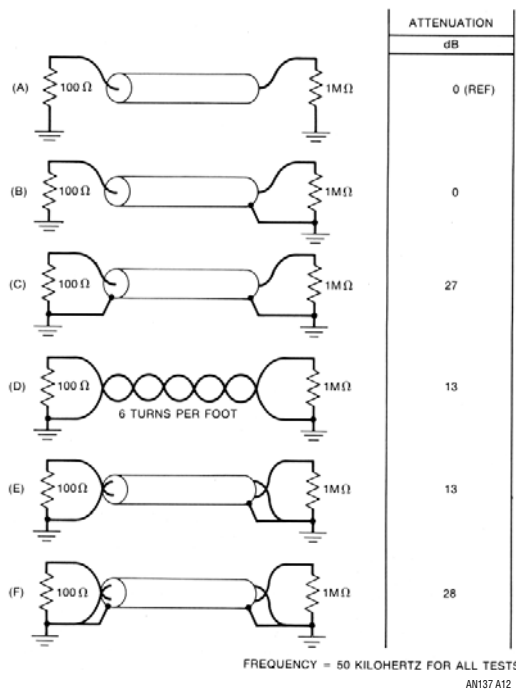


Figure A12.

The data in Figure A12 applies shielding and routing where the low sense is grounded at the sensor and receiver. This applies to the case where a power block is used and the low sense cannot be removed from the power ground return signal. Assume the sensor is the 100Ω resistor, and the receiver is the 1M resistor.

Case C represents routing the high and low sense in parallel with minimal spacing (low sense on both sides, and with low sense a ground), with a ground plane in parallel as the alternate path. Case F represents Case C with an additional shield. The minor difference in attenuation suggests that Case C is the better choice because routing is simpler. Case D represents a simple parallel routing, again with the low sense a ground.

This shows that the traditional parallel sense traces can be improved by routing the low sense (ground) on both sides of the high sense and grounding at both ends. This would apply to a power block when the low sense is tied to power ground in the module.

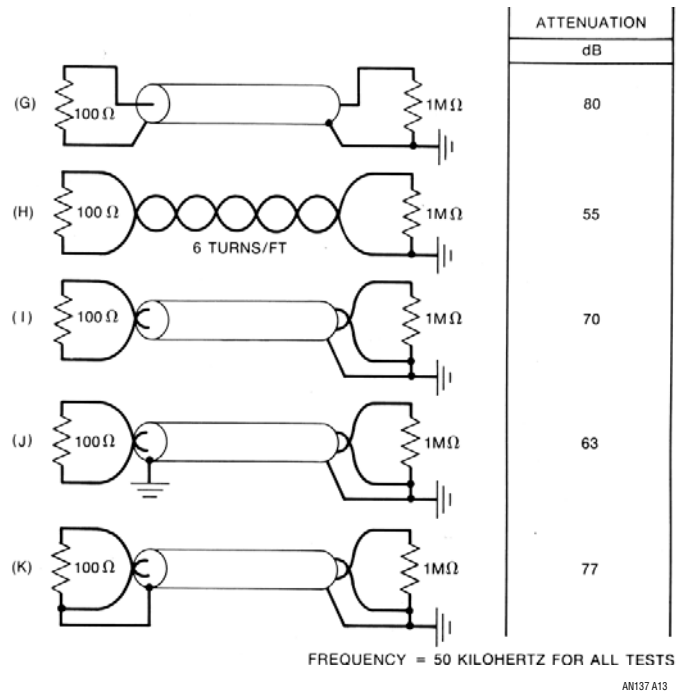


Figure A13.

Things are better when it is possible to ground at only one end.

As in the previous cases, the sensor is the 100Ω resistor, and the receiver is the 1M resistor. Case H represents the traditional parallel close routing. This is more than 15dB better than the previous case where you are forced to ground both ends.

Case G represents routing the low sense (ground) on both sides of the high sense. This is more than 50dB better than Case C and 25dB better than Case H. This is even 10dB better than Case I, which was the example from LTC2991 used in the capacitive coupling section. However, the LTC2991 low sense is high impedance and not ground as in this example. Therefore, don't disregard the LTC2991 data sheet.

55dB would be 8mV for a 5V noise source. 80dB would be 0.5mV for a 5V noise source. This is not an apples to apples comparison, as the experimental data was taken at 50kHz. However, the principles are clear. If you have the space, consider routing the low sense/ground on both sides of the high sense.

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Ground Coupling

Grounding loops are not typically the first source of noise coupling. However, if a sensor low sense is grounded at both ends, as when using a power block, a ground loop is formed. This loop can receive a magnetic field, hence inductive coupling, as discussed in the previous section. Not much can be done about this other than to make the shortest low sense route possible back to the receiver, and keep the layers between the trace and ground plane as thin as possible.

A more serious problem are share ground paths where one path contains high current. While it is possible to design a DC/DC converter using a parallel ground system (all loops have separate routes to the PGND pin), it is not typically done because at high switching frequencies ground signals will have inductive and capacitive coupling. The typical grounding system is a multipoint ground, almost always a ground plane, or a couple of very large plane sections that attempt to separate the gate loop from the power path loop.

For sensing, the main concern is allowing sensor low sense current to share any of these paths. If the singled grounded shielding is used, then the high current grounds are avoided. If a power block is used, current will be shared on the module and its ground pin. The best you can do is route the low sense from the module ground pin to minimize the shared path.

Most devices will have two grounds that are connected at a single point. One will be called signal ground, and one power ground. The shield used to prevent capacitive and inductive grounding is always tied to the signal ground. This prevents a shared ground path at the device end of the sensor connection.

Therefore, the worst scenario is a power block without a low sense pin, with a device that only has a power ground. The best case is a sensor with access to both high and low sense, where the low sense is not grounded, and the device has a signal ground and a power ground. Controlling these cases has to be done early in the design process during component selection, long before layout.