Wireless Precision Temperature Sensor Powers Itself, Forms Own Network, Enabling Easy Deployment in Industrial Environments

Kris Lokere

While the Internet connects people via a worldwide computer network, the Internet of Things (IoT) refers to a growing trend to create relatively simple devices that interconnect and share data independent of computer or human intervention. The IoT has the potential to increase efficiency, improve safety and enable entirely new business models in just about any facet of life or industry. For example, to reliably and efficiently operate an industrial plant, it helps to have as many monitoring (or control) points as possible—more sensors means better monitoring. The device-to-device networking of the IoT simplifies distribution and networking, making it easy to expand the number and reach of sensors throughout a plant.

Exponential increases in the number of sensors can be achieved by eliminating all cabling requirements through the use of robust, wireless, micropower sensors that run for years on a small battery. Better yet, eliminate the need to replace or recharge batteries. Instead, sensors harvest energy from their immediate environment, taking advantage of locally available energy sources, such as light, vibration or temperature gradients.

This article shows how to easily build a high resolution temperature sensor that runs on light energy when available and from a small battery backup when light energy is low. The design also includes a low power radio module that automatically forms a reliable mesh network to wirelessly connect sensors to a central access point.

DESIGN OVERVIEW

Figure 1 shows a block diagram of the self-powered wireless temperature sensor. The temperature sensor is based on a thermistor biased by a low noise LT6654 voltage reference. The 24-bit delta-sigma ADC LTC2484 reads the thermistor voltage and reports the result via SPI interface. The LTP™5901-IPM radio module takes on a number of tasks: it automatically forms an IP-based mesh network, its built-in microprocessor reads the LTC2484 ADC SPI port and it manages the power sequencing for signal chain components.

The LTC3330 is a low power dual switch-mode power supply that derives power from the solar panel when light is available, reverting to the battery backup when needed to maintain output voltage regulation. The LTC3330 also includes an LDO, which is used to duty cycle power to the temperature sensor.

The entire design has been implemented as Linear Technology demonstration circuit DC2126A. The complete solution, including battery and solar panel, fits inside a small plastic case measuring less than 7 cubic inches as shown in Figure 2.

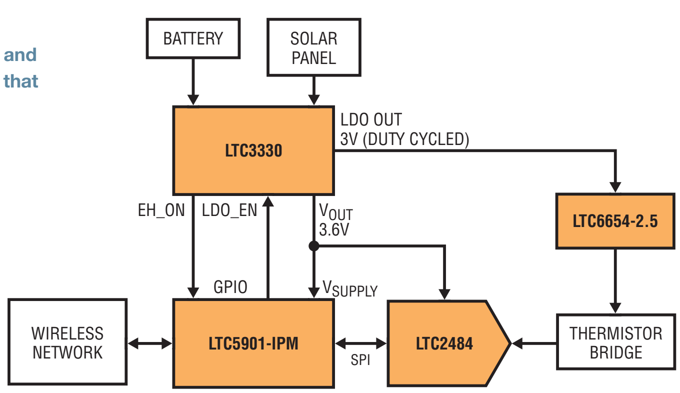


Figure 1. A wireless temperature sensor is formed by connecting a wireless radio module to an ADC, reference and thermistor. The circuit is powered by an energy harvester that can convert power from a battery or solar panel.

More sensors means better plant monitoring. The achievable number of industrial sensors can be multiplied by eliminating all cabling requirements through the use of robust, wireless, micropower sensors that run for years on a small battery. Better yet, eliminate the need to replace or recharge batteries. Instead, sensors harvest energy from their immediate environment, taking advantage of locally available energy sources, such as light, vibration or temperature gradients.

Figure 2. Entire self-contained, self-powered temperature sensor system fits into an enclosure less than seven cubic inches in volume. Battery, solar panel and wireless-networking controller are included. No external wires or connections are required. Installation is easy: place it somewhere. (a) Front of board showing signal chain, power and control circuitry and wireless mesh network module; (b) back of board with battery; (c) complete solution in enclosure with solar panel installed.

TEMPERATURE MEASUREMENT SIGNAL CHAIN IS ACCURATE AND DRAWS MINIMAL POWER

Figure 3 shows the signal chain—temperature measurement—components of the design, including the thermistor and ADC (with LT6654 precision voltage reference).

Thermistor

A thermistor can read temperatures over a wide range—they are simply resistors with a strongly negative temperature coefficient. For instance, US Sensor KS502J2 has a resistance of 5k at 25°C, and ranges from 88k to 875Ω over the –30°C to 70°C temperature range.

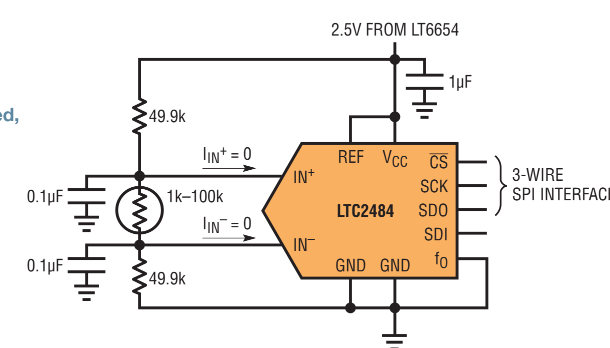
ADC and Accurate Voltage Reference

The thermistor is connected in series with two accurate 49.9k resistors, and biased up by the LT6654 precision voltage reference. The LTC2484 delta-sigma ADC measures the resistor divider ratio with 24-bit resolution. The ADC total unadjusted error is 15ppm, which for this thermistor slope corresponds to a temperature uncertainty of less than 0.05°C. This thermistor is specified with an accuracy of 0.1°C, so we can measure the temperature to that accuracy without any calibration.

The ADC noise is less than $4\mu V_{P-P}$, corresponding to less than a 0.005°C change in temperature. Therefore, with a calibration step, this system could be used to measure temperature to extremely fine resolution.

Because the ADC measures the ratio of thermistor voltage to a reference voltage, strictly speaking, an accurate reference is not required. Nevertheless, it

Figure 3. LTC2484 24-bit ADC reads the thermistor voltage. Because the input common mode voltage remains centered, this Easy Drive™ ADC draws no input current, which makes for an easy and accurate ratiometric reading.



The LTC3330 manages all power for this application. It includes two switch-mode power supplies and a linear regulator in a monolithic package. Here, a buck-boost converter draws power from the battery; a buck converter draws from the solar panel. The LTC3330's internal prioritizer ensures that solar power is used when available, preserving battery charge as much as possible. The LTC3330 also directly accepts AC energy harvesting sources, such as piezo crystals, which generate an AC voltage proportional to vibrational energy.

must be low noise, because variations in reference voltage during the ADC conversion period could produce errors.

The LTC2484 ADC features an Easy Drive™ input structure, meaning that net differential sampling currents during a conversion period are nearly zero. As a result, no measurement errors are induced from input sampling current flowing through the resistive thermistor network, which means no separate op amp buffer is required. Bypass capacitors provide a low impedance path at high frequency.

DUTY CYCLE POWER TO THE SIGNAL CHAIN TO CONSERVE POWER

Few applications require constant temperature monitoring. If one measurement per second or once per minute is enough, it makes sense in this micropower application to minimize the power draw during the mostly idle time. The resistor network draws up to 25μA from the 2.5V reference. To avoid this power loss between measurements, the power supply to the reference is duty cycled to be on only during measurement.

Determine the Required Duty Cycle

The RC time constant at the input of the ADC is about 5ms. By turning on the power 80ms prior to taking a measurement, full settling at the ADC input is ensured. In fact, since both input nodes turn on at the same slope, readings are accurate well before the theoretical settling time. The LT6654 is powered from the 3V LDO output of the LTC3330. The LTP5901-IPM's onboard microprocessor drives the LDO enable pin of the LTC3330 high and low at the correct times before and after performing a temperature reading.

The LTC2484 automatically enters sleep mode when not converting. The 1μA sleep current is low compared to the already low power of the wireless radio. Therefore, it is not necessary to duty cycle the power supply to the ADC. By keeping the ADC permanently powered from the same supply voltage as the LTP5901-IPM, the logic levels at the SPI interface are ensured to be the same.

Refreshing the Temp Reading Each Cycle

After providing a conversion result through the SPI port, the LTC2484 automatically starts a new conversion, and stores the result in its internal register until requested to read it again. This simplifies quick data turnaround in systems that read temperature frequently, but could make for a stale temperature reading in ultralow power applications with a significantly long interval between readings.

To ensure that the communicated temperature reading is always fresh, this application first toggles the $\overline{\text{CS}}$ and SCK pins to flush out any stale temperature reading from the ADC register, and automatically starts a new temperature conversion. The microprocessor waits until the conversion is finished and then reads the result through the SPI port. To save power, the system immediately proceeds to shut down the thermistor network (by turning off the LDO), even as the ADC automatically commences to the next temperature reading. This next temperature result is of no consequence, as it is flushed the next time the microprocessor requests a reading.

Table 1. Signal chain current consumption

CIRCUIT ELEMENT	CURRENT DRAW WHEN ACTIVE
LT6654 Reference	350μA
Thermistor Network	25μA
LTC2484 ADC	160μA
TOTAL	**535μA**

Table 2. Average signal chain current consumption based on read frequency

TEMPERATURE READ FREQUENCY	AVERAGE CURRENT
Once per second	170μA
Once per 10 seconds	17μA
Once per minute	2.9μA

The LTP5901-IPM performs two functions in this application: wireless networking and housekeeping. It includes the radio transceiver, embedded microprocessor and networking software. When multiple nodes of LTP5901-IPM are powered up in the vicinity of a network manager, the nodes automatically recognize each other and start forming a highly reliable, low power wireless mesh network. Each node can function as both a source of sensor information and as a routing node to relay data from other nodes toward the manager.

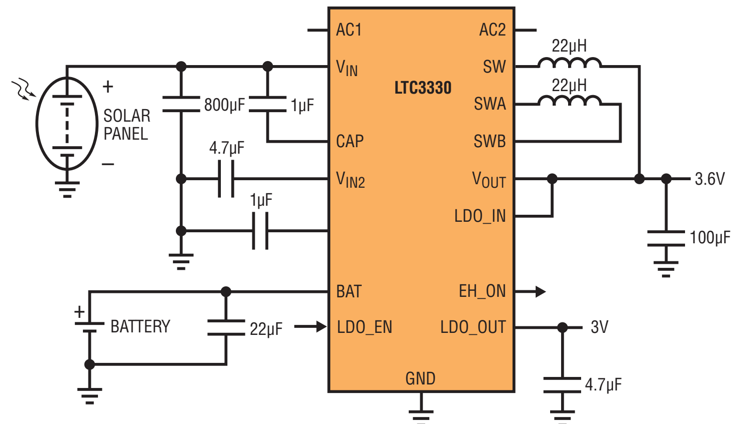


Figure 4. The LTC3330 takes power from the solar panel or battery, automatically prioritizing between the two sources to maintain a regulated output voltage. An additional LDO output is controlled by a logic input pin, which is used to duty cycle power to the temperature sensor. The LTC3330 generates an output flag to indicate whether solar or battery power is being used.

Calculating Signal Chain Power Consumption

The overall power consumption of the temperature sensor circuitry can be estimated by determining the total charge consumed and dividing by the period of temp reading, as follows:

1. Sum the current of the reference (350μA), thermistor network (25μA), and ADC (160μA when converting) for a total of 535μA (Table 1).
2. Determine the total charge consumed by considering how long this current is present. The ADC takes about 140ms for a conversion, with a precursor 80ms for the reference and thermistors to settle. Add some time for the SPI readout, and we are at about 300ms on-time. Consuming a current of 535μA during 300ms corresponds to a charge of 160μC. We should add to this the charge needed to charge up the 4.7μF supply bypass capacitor to the voltage reference, because this node is recharged from 0V to 3V with every reading. This 14μC of charge brings the total to 174μC per temperature reading.
3. A rate of one temperature reading every 10 seconds works out to an average current consumption of 17μA. Other examples of average supply current are given in Table 2.

SINGLE POWER IC FOR SOLUTION-WIDE POWER MANAGEMENT

The LTC3330 manages all power for this application, as shown in Figure 4. It includes two switch-mode power supplies and a linear regulator in a small monolithic package.

Two Switch-Mode Converters Handle Battery and Solar Inputs

A buck-boost converter can take power from the battery to maintain a regulated output voltage (set to 3.6V for this application). A separate buck converter can take power from the solar panel to regulate the output voltage to the same level. An internal prioritizer ensures that solar power is used when possible, drawing power from the battery only when needed. For other applications, the LTC3330 also supports AC energy harvesting sources, such as piezo crystals, which generate an AC voltage proportional to vibrational energy.

The LTC3330 draws less than 1μA quiescent current, a good fit for this mostly idle, low power wireless application. The power loss in the operating power supply is a small fraction of the total power—most of the power is available for the work of the temperature sensor and wireless network.

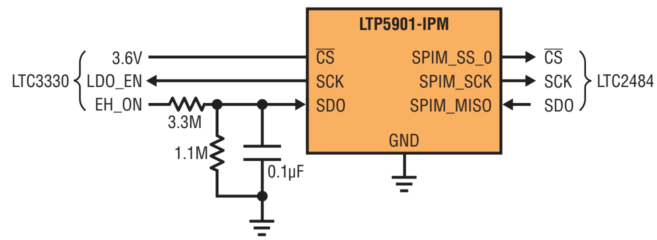
LDO Powers and Duty Cycles Signal Chain

In addition to the two switch-mode power supplies, the LTC3330 includes an LDO with a separate LDO enable pin. This enable feature is handy for this low duty cycle application, where the voltage reference and thermistor network are powered from the LDO to minimize switching noise. The LDO enable feature allows the application to simply toggle power to the signal chain on and off, even as the switch-mode power to the wireless radio is always on.

Even though the wireless radio does not consume much power in between

The LTP5901-IPM includes an ARM Cortex-M3 microprocessor core, which runs the SmartMesh IP networking software. This core is highly programmable via user-supplied application firmware, making it possible to build a wide variety of solutions without any additional microprocessors.

Figure 5. The LTP5901-IPM requires only a few simple connections to manage networking and housekeeping tasks for the application. All wireless networking functions, including firmware and RF circuitry, are built in. A 3-wire SPI master communicates with the LTC2484 SPI port. A GPIO pin (DP2) controls power sequencing to the sensor. The built-in ADC acts as a convenient level translator to read the energy harvesting status flag EH_ON from the LTC3330.



transmissions, it is very important that it always remains biased up, to keep timers running correctly so that the entire network remains time-synchronized. The microprocessor inside the wireless radio sequences the LDO enable pin at the correct times to prepare the signal chain for a temperature reading.

Output Flag Indicates Battery or Solar Panel Draw

The LTC3330 provides an output flag (EH_ON), which tells the system whether power is being drawn from the battery or from the solar panel. It can be informative for the end user to have real-time access to this information. Therefore, we let the microprocessor inside the wireless radio read this output flag and transmit it through the network, along with the temperature data itself.

The logic level for this EH_on output is referred to an internal bias voltage of the LTC3330, which varies depending on operating mode and can be higher than 4V. Rather than connecting that output pin directly to the lower-voltage logic input of the wireless radio, we divide it down and feed it into a built-in 10-bit ADC (part of the microprocessor). In this case, we just use that ADC as a comparator to indicate which power source the LTC3330 is using.

COMPLETE WIRELESS NETWORK WITH A SINGLE MODULE

The LTP5901-IPM is a complete wireless radio module, including the radio transceiver, embedded microprocessor, and networking software. Only a few connections are required to create a self-forming wireless network and data gathering/communication system with this module, as shown in Figure 5.

Its physical format is a small printed circuit board, which can be easily soldered onto the main board containing the signal chain and power management components.

The LTP5901-IPM performs two functions in this application: wireless networking and housekeeping via microprocessor. When multiple nodes of LTP5901-IPM are powered up in the vicinity of a network manager, the nodes automatically recognize each other and begin forming a wireless mesh network. The entire network is automatically time synchronized, which means that each radio is only powered on during very short, specific time intervals. As a result, each node can function not only as a source of sensor information, but also as a routing node to relay data from other nodes toward the manager. This creates a highly reliable, low power mesh network, where multiple paths are available from each node to the manager, even though all nodes, including the routing nodes, operate on very low power. A typical range for this radio technology is 100m between nodes, with broader ranges possible in favorable outdoor conditions.

The LTP5901-IPM includes an ARM Cortex-M3 microprocessor core, which runs the SmartMesh IP™ networking software. This core is highly programmable via user-supplied application firmware, making it possible to build a wide variety of solutions without any additional microprocessors. In this example, the LTP5901-IPM's microprocessor manages power sequencing to the temperature sensor by turning the LDO of the LTC3330 on and off to conserve power. The LTP5901-IPM communicates directly to the SPI port of the 24-bit ADC. Finally, the LTP5901-IPM reads the power status output flag (EH_on) from the LTC3330, which indicates whether solar light or battery is used to power the circuit.

A combination of easy-to-use, high performance power management, and wireless networking devices enable the design of self-contained, *completely wireless* sensor products. The time-synchronized wireless mesh network ensures that minimal power is used to reliably transmit data from node to node, and the on-chip microprocessor can further save power by duty cycling power to the sensor circuitry.

Power consumption of the wireless radio can be estimated using the "SmartMesh® Power and Performance Estimator" spreadsheet found at www.linear.com/products/smartmesh_ip. For a typical network of 20 motes, where 10 motes have a direct wireless connection to the manager (1-hop), and 10 others have an indirect connection to the manager (2-hop), average power consumption is about 20µA for the 2-hop nodes and 40µA for the 1-hop nodes. These numbers are for each node reporting temperature once per 10 seconds.

1-hop nodes consume about twice as much power as 2-hop nodes because they transmit not only their own sensor data, but also act as routing nodes to forward the sensor data from some of the 2-hop nodes. The above-mentioned power levels can be reduced by about a factor of two if the advertising feature is turned off. Once advertising is turned off, the network no longer recognizes new nodes that want to join the network. Other than that, there is no impact on network operation.

OVERALL POWER CONSUMPTION

Total power consumption depends on a number of factors, including how often each sensor measures temperature, and how the nodes are configured in the network. Typical power consumption for a sensor node reporting once per 10 seconds is less than 20µA for the sensor portion and can be 20µA for the wireless radio, for a total average load current of about 40µA.

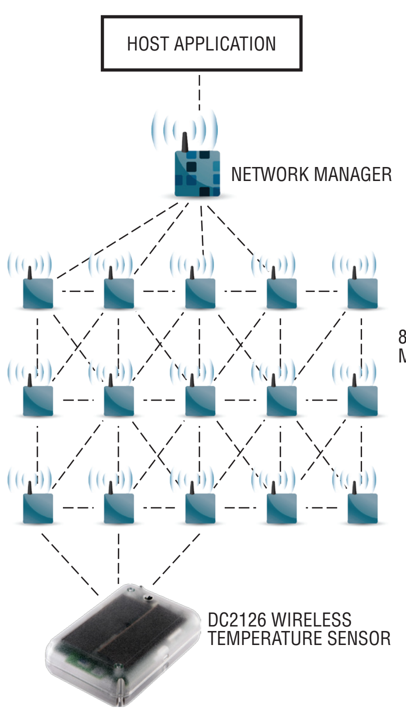


Figure 6. Precision temperature sensor easily drops into robust SmartMesh IP wireless mesh network.

A small 2-inch by 2-inch solar panel (such as the Amorton series) can generate 40µA at relatively moderate indoor lighting conditions (200-lux); much more in bright light. This application could run entirely on solar power in a variety of environments.

Otherwise, if the circuit must run entirely on battery power, a 2.4Ah AA battery (such as the Tadiran XOL series) could power this application for nearly seven years.

In low or variable light conditions, the circuit automatically toggles back and forth between solar power and battery power, so that any available solar power is used to extend the life of the battery.

CONCLUSION

A combination of easy-to-use, high performance power management, and wireless networking devices enable the design of self-contained, *completely wireless* sensor products. The time-synchronized wireless mesh network ensures that minimal power is used to reliably transmit data from node to node, and the on-chip microprocessor can further save power by duty cycling power to the sensor circuitry. Efficient, highly integrated power management ICs can power the application entirely from a small solar panel, or for many years from a small battery. ■