By Margery Conner, Technical Editor

ULTRALOW-POWER SYSTEMS DESIGNED FOR THE LONG HAUL

Run for your

SYSTEMS CAN ACHIEVE AN AVERAGE CURRENT DRAIN ON THE ORDER OF 1 μA BY RELYING ON A LOW DUTY CYCLE AND BY MINIMIZING THE POWER NEEDS OF THEIR PROCESSOR, SOFTWARE, AND ANALOG INTERFACE.

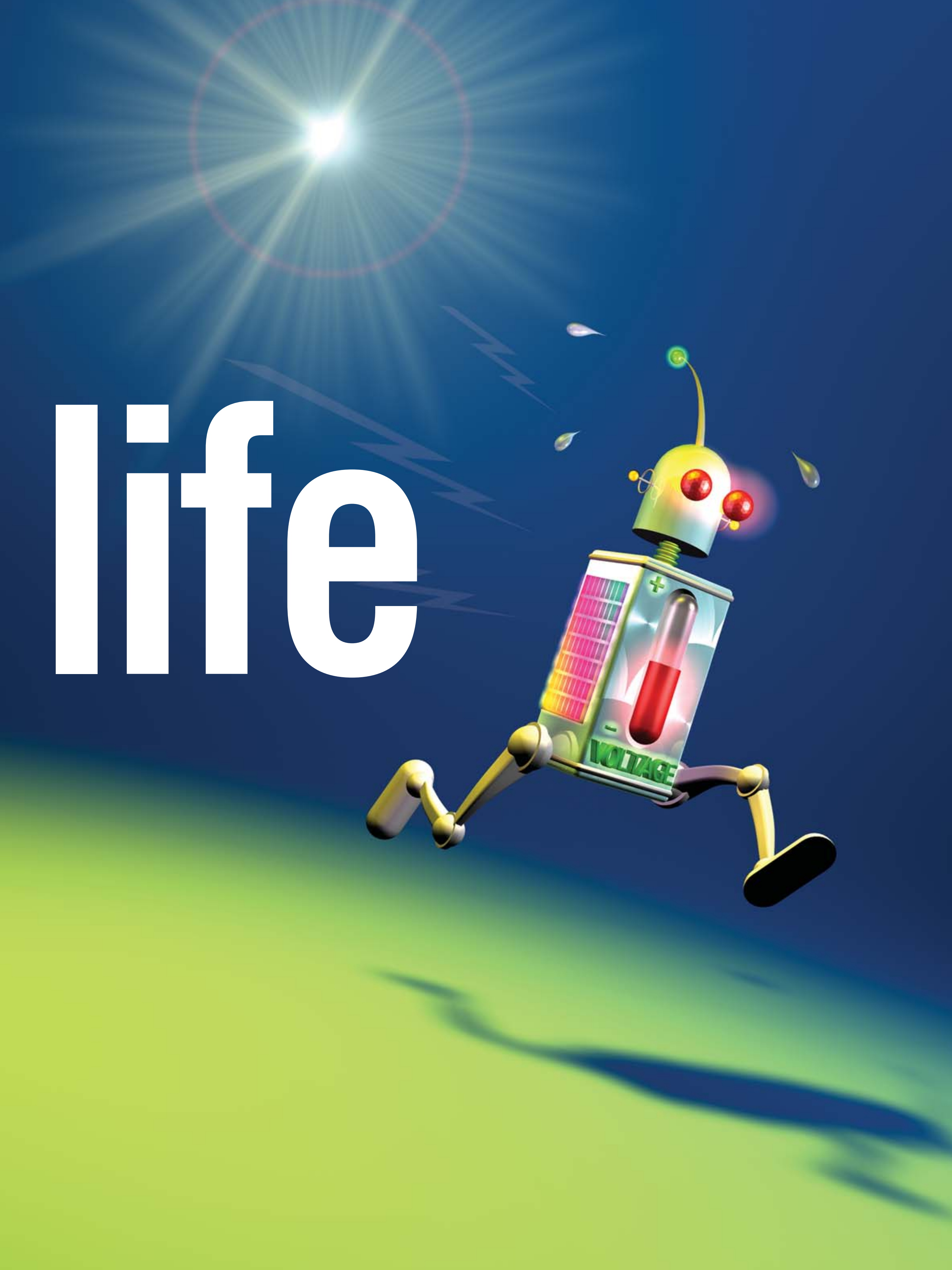
The needs of portable consumer devices have until recently driven low-power design methods for electronic systems. In these devices, the power source is usually a lightweight battery, and the need to fit into a pocket or briefcase dictates limits on size. Although these power constraints are more rigorous than for a system that relies on power from a wall plug, the power is still relatively plentiful. After all, users can recharge that iPod or cell phone every night.

What if users could never recharge—or even replace—the system battery? This scenario faces designers of systems deployed in a remote field installation where replenishing the battery is not an option. A wireless-sensor network, often called a smart-sensor, or dust, network, is one such application: The average current consumption of each independent node is around 1 μA.

Less exotic consumer applications can also face severe power constraints. One example is the common home thermostat. Designing it so that users can replace the battery adds both a layer of complexity to the homeowner's instruction manual and the expense of the added ruggedness and access ports on the case, so thermostats are often sealed units. Juan Alvarez, Texas Instruments' MSP430 marketing manager, explains the straightforward calculation of a thermostat's energy budget: "A small lithium-ion battery has about 220 mA-hours. If you achieve an average system current consumption of 2.5 μA, that works out to about 10 years of battery life." At the end of 10 years,

Illustration by Chuck Mackey

life



the homeowner replaces the thermostat rather than replacing the battery.

The prime characteristic of a system that can operate on the order of 1 μA of average current is low duty cycle. Such systems are asleep for more than 99% of their life with brief intervals of activity when they wake up, poll their sensors, process and communicate sensor measurements, and then return to a sleep state. When designing for such low-duty-cycle, ultralow-power systems, designers have two main areas with decidedly different characteristics in which to conserve power: digital communication and processing and sensor-amplifier and interface circuitry.

Communication takes a significant amount of the power budget for a wireless-sensor network. Developers designed most popular wireless protocols for systems having relatively unlimited power. For example, a protocol such as 802.11, with its always-on listening mode, is impractical for a low-duty-cycle network. Sokwoo Rhee, chief technology officer at wireless-sensor-network designer Millennial Net, says that the company considered other wireless-network protocols, such as Zigbee, but found that the communication required too much power. Millennial Net instead created its own protocol for wireless-sensor networks. Says Rhee, "We had to minimize the number of control packets sent back and forth to keep track of the topology. A wireless-sensor network needs to minimize overhead and be really efficient at discovering and rediscovering the network. You're saving power because you're not running a microprocessor for all this [inefficient-network] overhead."

AT A GLANCE

▷ Ultralow-power devices must operate without the need to change or recharge batteries.

▷ A low duty cycle is key; the system should spend more than 99% of its time in a "sleep" state.

▷ The system is not always constrained to a "low-power" processor.

▷ Several design techniques minimize sensor-interface power.

It was worth the effort to create a new protocol, because a ripple effect occurs beyond just the savings of microprocessor time and attendant power. According to Rhee, the company tried to keep the code footprint small. Protocols such as Zigbee have footprints that are more than double the size of Millennial Net's proprietary footprint. The protocol fits into a small memory space, so it uses a smaller microprocessor, which draws less power and allows the company to meet its power-conservation goals. The company selected Microchip's PIC16/8LF controller chip for its power efficiency. Future processors in low-duty-cycle, ultralow-power designs may take advantage of low-threshold-design techniques (see **sidebar** "Subthreshold design holds low-power promise").

TRIPPED UP?

Surprisingly, it's sometimes unnecessary to select a power-optimized system processor for low-power designs. Eli Weinstein, chief technology officer of AvalonRF, another wireless-sensor-network manufacturer, also points to the low duty cycle as being key in allowing ultralow-power requirements. But AvalonRF's system processor must be powerful enough to handle capturing, processing, and transmitting a snapshot that a node takes. A sample application for the device is monitoring secure but remote installations, such as a reservoir or a power station. The system must be able to function for as long as 10 years, running off a primary lithium battery. If a sensor trips, the device wakes up, captures, processes, and transmits an image to a decision-maker who determines what triggered the event.

Weinstein says that, although Analog Devices' 32-bit Blackfin microcontroller is not what most would classify as a low-power processor, AvalonRF designers use a Blackfin ADF 7020 operating with a duty cycle so low that the average current drain can be less than 1 μA. "If you turn off the clock on the Blackfin, it's very low-power," says Weinstein. It's important for low-duty-cycle operation that the processor can stop the clock in power-saving

SUBTHRESHOLD DESIGN HOLDS LOW-POWER PROMISE

Speed is the overriding goal for many processor designers. However, that's not the case for Alice Wang, PhD, who examines the trade-off between energy and speed for an FFT processor (**Reference A**). The application for the processor is powering a node in a wireless-sensor network that harvests its system energy from the environment. Due to the requirements for energy scavenging, the key metric is minimizing energy dissipation rather than processor speed. Wang's research focuses on the use of subthreshold design, which runs circuits at a voltage supply that is lower than the threshold voltage of the device.

Wang's processor runs as low as 180 mV compared with a typical processor threshold range of 1 to 1.2V. The relationship between voltage and speed is exponential: A system running at 1 GHz at 1.2V would be running in the kilohertz range. Because of the trade-off of power for speed, subthreshold design is a candidate for future low-duty-cycle systems.

Wang's processor architecture also employs other energy-saving characteristics, such as variable bit precision, which allows the processing precision to degrade based on the immediate needs of the processing function. Wang says that lowering the voltage to the subthreshold level is the biggest factor in achieving the least energy. Although Wang's research uses a custom processor, her findings apply to off-the-shelf parts, as well. Look to see more designers applying subthreshold approaches in the future as ultralow-power devices, which must harvest energy from their environment, become increasingly common.

REFERENCE

A. Wang, Alice, PhD, and Anantha Chandrakasan, "A 180-mV Subthreshold FFT Processor Using a Minimum Energy Design Methodology," *IEEE Journal of Solid State Circuits*, Volume 40, No. 1, pg 310, January 2004, www-mtl.mit.edu/research groups/icsystems/pubs/journals/2005_wang_jssc_jan.pdf.

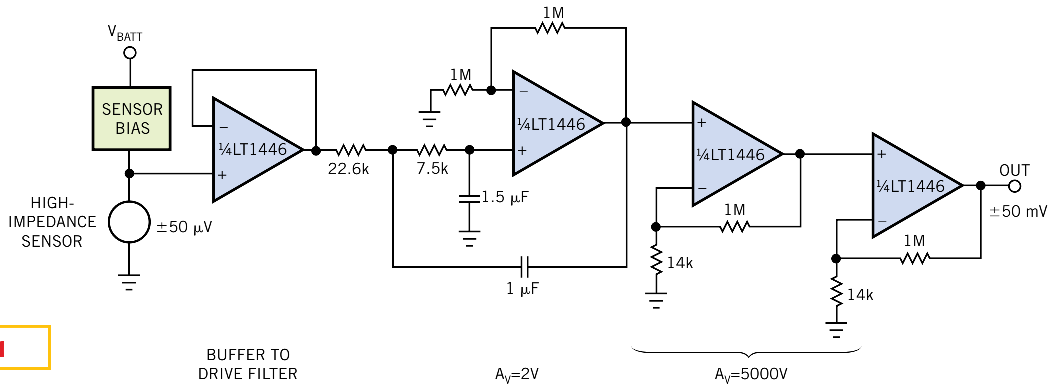


Figure 1

Signals from sensors in ultralow-power systems are often small and noisy. Placing the filter stage in front of the gain stage saves power.

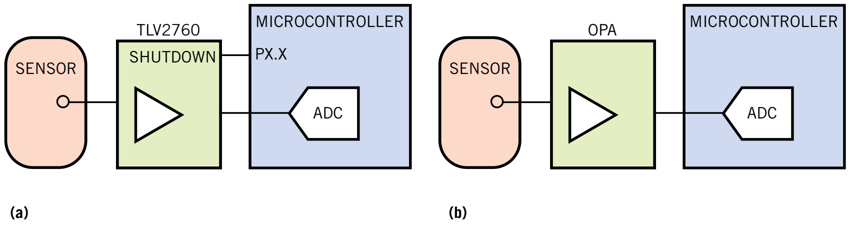


Figure 2

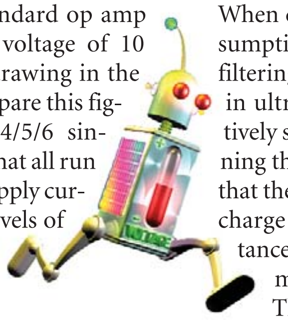
Texas Instruments' TLV2760 has a shutdown spec of 0.01 µA (a). This comparison is for a portable medical device that users employ four times per day for one minute each time, yielding an effective duty cycle of 4/1440—less than 1% on-time. The always-on OPA microcontroller has active and quiescent modes of 1 µA (b).

mode and then instantly respond; some processors must go through a lengthy, power-consuming restart procedure.

The sensor-to-processor circuitry for these ultralow-power, low-duty-cycle systems must likewise be low-power. The goal is to select an amplifier that has just enough performance to meet the system's signal-processing needs and requires the lowest power for that level of performance. The op-amp parameters that especially influence power consumption are noise performance, slew rate, and output-current drive. In addition, although less critical, bias current and supply-voltage droop also have an impact.

Unfortunately, low-power-consumption amplifiers have higher noise specifications than standard op amps. Tim Regan, signal-processing-applications manager for Linear Technology, explains how design constraints exacerbate the devices' noise problem: "When you starve all the amplifier's transistors for current, you usually have to include very large [internal] resistors on the order of 2 to 3 MΩ. Designers of ultralow-power systems have to accommodate that. Large resistors mean significant thermal noise."

For example, a standard op amp might have a noise voltage of 10 nV/$\sqrt{\text{Hz}}$ at 1 kHz, drawing in the milliamp range. Compare this figure with the LT1494/5/6 single/dual/quad amps that all run at only about 1-µA supply current but have noise levels of 185 nV/$\sqrt{\text{Hz}}$, significantly higher.



To accommodate the inescapably higher noise of low-power op amps, system designers must often add filtering. When designing for normal power consumption, designers usually try to avoid filtering because of the added delay, but in ultralow-power designs, time effectively slows down: A by-product of running the amplifier at such low current is that there isn't much current available to charge the amplifier's internal capacitances; only nanoamps are available to move an op amp's internal nodes.

Thus, low-power op amps have low slew rates, measured in millivolts per second rather than volts per second. "As a low-duty-cycle-system designer," says Regan, "the one attribute you have to have is patience, because everything is moving slowly. But, on the other hand, this allows you the time to filter because you're not going to get much bandwidth out of your system anyway. So go ahead and filter out that noise. It kind of eases the pain of the higher noise design."

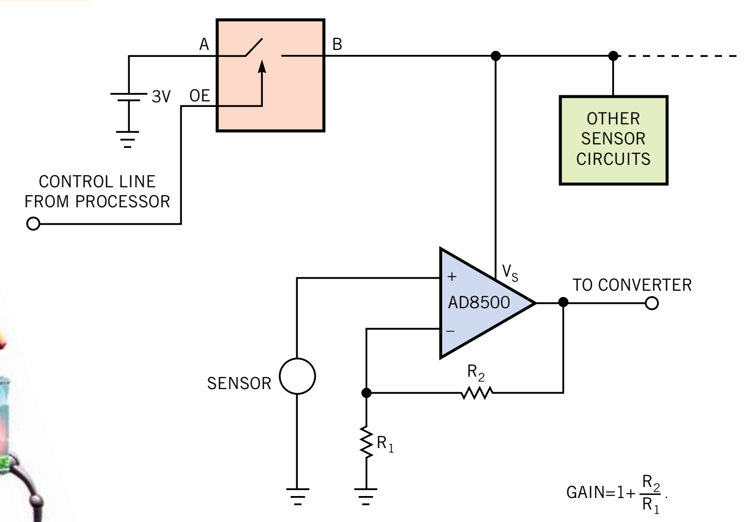
The need to amplify the sensor signal depends on its voltage level. Says Eric Nolan, product-marketing manager for Analog Devices, "Typically, if you're in the hundreds-of-millivolts-to-volts range at the sensor you might need only to buffer

"FLEAPOWER" DESIGN IDEAS SHRINK CIRCUIT-POWER NEEDS

Although this article focuses on the use of ultralow-power-design techniques for systems that must either contain their own power in the form of a battery or harvest it from their environment, many circuits can benefit from miserly use of power. Over the years, *EDN*'s Design Ideas have contributed to the effort of low-power design with a number of circuits dubbed "'fleapower." Visit www.edn.com/fleapower to review them and their techniques for consuming the minimum power possible in these applications:

- "Solar-powered motor runs on 10 nA,"
- "V/F converter draws fleapower,"
- "Motor controller uses fleapower,"
- "Low-battery indicator uses fleapower,"
- "Fleapower flasher draws less than 50 µA,"
- "Reset generator uses "'fleapower,'"
- "Fleapower circuit detects short circuits,"
- "Continuity buzzer is frugal with power," and
- "Fleapower oscillator consumes only 1 µA."

Figure 3



Shutting down power to the sensor as well as its amplifier saves system power in “sleep” mode.

the signal before it goes into a converter. To minimize power consumption you want to use higher value resistors so that you eliminate additional dc current paths.” Plus, he adds, “If you're just doing buffering, you can probably get away with using a noninverting-unity-gain configuration; you tie the output feedback directly to the inverting-amplifier pin. In that case, you're not driving any resistive loads with the amplifier, other than what comes off the output that you're driving.”

If the sensor-output voltage is in the low-millivolts-to-microvolts range, it requires some amplification. The best way to amplify the signal, suggests Linear Technology's Regan, is to do the gain in multiple stages and do all the filtering in the first stage (**Figure 1**). “When you add filter capacitors, if you have large voltage-swing changes, you have to charge and discharge those external capacitors that are doing your filtering. So, if you can put the filtering in the first stage when ... just a few microvolts are coming in, you're not going to waste current in charging and discharging filter capacitors. You can follow that filter stage with conventional resistive-gain stages.”

In these low-duty-cycle systems, the op amps spend most of their time doing nothing, so it's worthwhile to minimize their doing-nothing current drain. For many standard op amps, you can find out their no-load current in their quiescent-current specification, which is the current the device requires when it isn't under load. However, op amps targeted for low-duty-cycle operation can have a shutdown pin, which forces the op amp into an even lower current mode. The savings in current is significant: A typical specification for quiescent current is 1 μA, whereas shutdown current is about 0.01 μA.

SHUTDOWN OPTIONS EXIST

TI's Alvarez suggests considering op amps with this feature (**Figure 2**). “At the price of the additional pin, you save almost an order of magnitude [of current]. With shutdown, you actually force the device to go inactive and wake it up to turn fully on.”

Shutdown pins are not panaceas, however. Nolan of ADI, cautions, “Amplifiers take a certain amount of time to bias up into proper operation, and, typically, the lower the normal power consumption, the longer it takes it to turn on, especially if you use the really low-power amplifiers to begin with.” Plus, shutdown affects only the op amp itself; the sensor circuitry is still dissipating power. Nolan says that designers often prefer to use an external switch and turn off power to both the amplifier and the sensor circuitry (**Figure 3** and **references 1** and **2**).

Smart-sensor wireless networks, such as Millennial Net's 916-MHz product family, must operate in remote locations, where changing the battery is not an option. The power requirement for the small end node (upper right) is on the order of microamps.

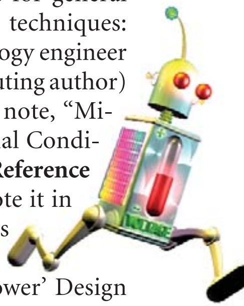
Linear Technology's Regan agrees with this caveat regarding the “spin-up” time of a shutdown op amp, pointing out that most shutdown turn-on and -off times are not guaranteed: Manufacturers specify only typical times. Long turn-on and -off times, he says, “affect the on time of a low-duty-cycle system, resulting in a reduction in total lifetime of the battery. Instead of lasting 10 years, it might last only five.” Regan suggests that you make sure that your design can live with the turn-on and -off times.

The third factor in designing with op amps for low-power, low-duty-cycle systems is drive current. A standard op amp might have a short-circuit current of 20 mA compared with a low-power op amp's 500 μA to 1 mA. Drive current goes even lower with systems requiring less than 3V. A standard op amp with a 5V supply can typically provide 10 mA of current, but in an ultralow-power system operating from a single power cell at, say, 1.8V, it can provide only 1 mA. Says Regan, “The device doesn't have the voltage headroom to fully bias the current source to provide the base current to the output transistor. These low-power devices can't source and sink as much current.”

Battery-output voltage over time also

affects drive current. Small coin batteries, such as a lithium primary cell, start out fully charged at about 3V and continue to emit current even when the voltage drops down as low as 1.5V. System designers need to select devices that are tolerant not only of a low supply voltage, but also a voltage range that can start out high and fall as the battery drains. In ultra-low-power systems, low currents eliminate the need for power-conditioning parts, such as regulators, so that the system can run directly off the battery.

Regan suggests a source for general low-voltage analog-design techniques: Read fellow Linear Technology engineer (and popular *EDN* contributing author) Jim Williams' application note, "Micropower Circuits for Signal Conditioning," available online (**Reference 3**). Although Williams wrote it in 1987, the principles it covers are still relevant today. (Also see **sidebar** "'Fleapower' Design Ideas shrink circuit-power needs.")□



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3. Williams, Jim, "Micropower Circuits for Signal Conditioning," Linear Technology Corp, April 1987, www.linear.com/pc/downloadDocument.do?navId=H0,C3,P1247,D4118.

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