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Self-powered wireless sensor nodes: Among other things, a load management feat

Distributed, self-powered, micro-scale, wireless sensor networks promise to revolutionize large-scale systems, changing the way they are studied, built, monitored, and controlled.

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Distributed, self-powered, micro-scale, [wireless](#) sensor networks promise to do for large-scale systems what the integrated [circuit](#) (IC) did for computers and portable devices, changing the way they are studied, built, monitored, and controlled. In biomedical applications, encapsulated sensors can be implanted or swallowed to [monitor](#) various body functions and deliver medication on-demand. Industrial systems could distribute sensors throughout a plant or facility to accurately and uniformly control humidity, temperature, and countless of other parameters, and even perform system prognosis and initiate self-healing sequences. Sensors used in military vehicles can gather security-threatening information, such as the presence of toxic, explosive, or electromagnetic interference (EMI), to not only warn and automatically react but to also study the way systems behave once they are deployed in the field, allowing next-generation designers to improve the way the systems are built. Key enabling attributes to this technology are its high sensor-density and non-invasive features, which present challenges in the form of integration (including micro-scale energy sources); efficient power-conditioning microelectronics; and micro-Watt, load-managed transceivers, sensors, and supporting circuits, the composite of which is illustrated, in general form, in Figure 1.

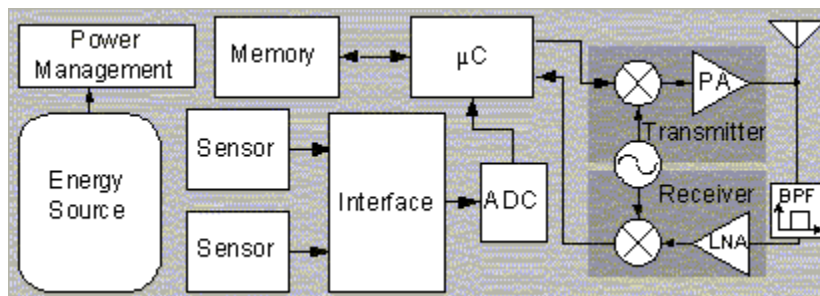


Figure 1. Complete self-powered, wireless sensor node system

Integration

Integrating the energy source into a micro-chip is arguably the first challenge to confront. The device must pack sufficient energy into a small volume of space to yield operational lives on the order of days, months, and even years. To this end, thin-film lithium-ion batteries (Li Ion) are conformable and yield reasonable energy levels (that is, lifetimes), but not enough to sustain a practical electronic system when constrained to such dimensions, which is why micro-scale MEMS fuel cells are promising. Fuel cells, however, fall short in power, when compared to Li-Ion technology under similar space constraints. A hybrid micro-scale MEMS fuel cell-thin-film Li Ion source is therefore optimal [1]. Managing such a hybrid source requires multi-directional energy-flow and power-conditioning systems, as shown in Figure 2, wherein, as an example, a current-regulated boost converter is used to transfer energy from a 0.8 - 1.4V, two-stack fuel cell to a 2.7 - 4.2V Li Ion and a voltage-regulated buck (or boost) converter to transfer energy from the Li Ion to the wireless sensor load. The total energy and peak power the system can store and deliver is still limited to its overall dimensions, and a low power-consuming load is still required. Harvesting energy from the environment, be it kinetic, solar, and/or thermal, *in situ* can potentially increase the total energy of the system, but not the peak power available to the load, since a harvester of this scale can only garner pico-Joules at a time.

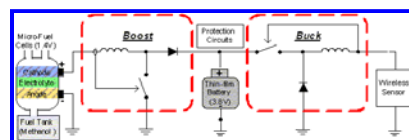


Figure 2. Hybrid micro-scale MEMS fuel cell-thin-film Li Ion source system

Integrating the antenna, sensors, and power inductors shown in Figures 1 and 2 also presents challenges. For one, the antenna's efficiency is closely

linked to its geometry and driving carrier frequency: its size must be on the order of, or longer than, the carrier wavelength. Mainstream CMOS devices, however, provide gain up to approximately 1GHz, considerably below the optimal range of micro-scale antennas, which radiate efficiently at or above 50GHz. GaAs or SiGe technologies are optimal for maximum efficiency, but the mediocre efficiency levels (for example, less than maybe 10%) micro-scale antennas can produce when driven with CMOS-compatible carrier signals must be considered for cost reduction [3]. Similarly, high-quality inductors are useful in maximizing the efficiency of power-conditioning circuits, yet on-chip inductors have poor quality factors (Q is less than 5) and relatively low inductances (less than 100nH). Fortunately, state-of-the-art micro-Henry off-chip inductors with reasonable Qs now conform to 2mm x 2mm x 1mm dimensions, making co-packaged solutions and integration possible. Similarly, while on-chip piezoelectric and temperature sensors are possible, a wide-range of higher performance *co-packagable* pressure, piezoelectric, and humidity sensors also conform to micro-scale dimensions.

Load Management

Even if the fundamental limits of energy and power density are achieved with fuel-cell and Li-Ion technologies (including nuclear batteries), given the dimensional objectives of a micro-scale wireless sensor, total energy and peak power are considerably constrained, so special consideration must be given to the load, in this case, the sensor and wireless telemetry functions (Figure 1). Unilaterally decreasing power, however, degrades signal-processing accuracy and integrity in the form of feedback error (lower loop gain), lower bandwidth (less current with which to charge and discharge parasitic capacitors), and lower signal-to-noise ratio (SNR), among other factors. Load-management schemes are therefore adopted to battle power consumption at all levels, system, circuit, and device.

The first line of defense against power consumption is to duty-cycle the various functions of the system to decrease power and energy demands. Sensing temperature and humidity, for instance, need not be continuous because changes are slow, on the order of milli-seconds or slower. Similarly, telemetry need not be awake or send packets of information constantly, or at the same time sensing is performed. Only sensing a fraction of the time and transmitting data even less frequently during sensor off-times reduce both average and peak power, the former of which translates to less energy. The application, however, will determine the extent to which duty-cycling can be applied, which is why the battle against power demands is multifaceted.

Operating transistors in their sub-threshold region and applying system-level feedback and serial signal-processing techniques can also maximize the power-accuracy (and functionality) ratio of a system. Working in sub-threshold implies MOS devices are weakly inverted and conducting minimal current densities, which implies increased threshold voltage mismatch errors and lower bandwidth, the latter of which may be less restraining because the bandwidth requirements for temperature, humidity, and other parameters of the sort are relatively low. Additionally, the degradation in accuracy of a single wireless sensor node may be compensated with localized feedback loops and a densely packed network of sensor nodes.

The third line of defense is reducing the voltage across the sensor and telemetry electronics, since power is directly proportional to this voltage. Even when the system is completely or partially disabled, lower supply voltages induce lower leakage currents, which may be a significant power sink because duty-cycling is extensive and the device is consequently idling most of the time. Its drawbacks are lower dynamic range and lower gate-drive, in other words, less noise margin and lower precision and larger switches (larger parasitic capacitors) and therefore lower speed, larger footprint, and increased thermal noise, the latter of which further degrades dynamic range and precision. Ultimately, for a practical solution, the system must only achieve the accuracy and speed required, and no more, challenging the designer to fully justify all system-level specifications and requirements and to avoid over-designing for the mere sake of comfort.

Before unilaterally duty-cycling, forcing circuits to operate in sub-threshold, and reducing supply voltages, however, power- and energy-hungry functions must be identified and tackled first, as they constitute the bottlenecks of the system. Applying these techniques to a function that is seldom used and/or consumes little power to begin with has minimal impact on operational life and therefore adds little value to the objective at hand. As is the case in most portable consumer electronics, telemetry is one such power-hungry task.

Telemetry

The in-package energy source's power density (that is, peak power) is pushed to its limits when a wireless telemetry function is included in the system. In particular, the power amplifier (PA) must drive sufficient energy into the transmitting antenna for the receiving antenna and subsequent electronics to discern the signal over the noise power (P_{Noise}) present. In a typical wireless system, as illustrated in Figure 3, the supply power (P_{Bat}) required to drive the signal through the PA, transmitting antenna, and receiving antenna depends on the efficiency losses across the signal path and the minimum signal power needed at the receiver (P_{RX}) to interpret the receiving data (that is, signal-to-noise power ratio SNR requirement: P_{RX}/P_{Noise}):

$$P_{RX} = P_{Bat} \left(\frac{P_{TX}}{P_{Bat}} \right) \left(\frac{P_{Rad}}{P_{TX}} \right) \left(\frac{P_{Inc}}{P_{Rad}} \right) \left(\frac{P_{RX}}{P_{Inc}} \right) = P_{Bat} \eta_{PA} \eta_{AntTX} \eta_{Rad} \eta_{AntRX} \geq SNR \cdot P_{Noise}$$

(1)

where P_{TX} is the signal power driven into the transmitting antenna, P_{Rad} the signal power radiated out of the transmitting antenna, P_{Inc} the incident power received by the receiving antenna, η_{PA} PA efficiency P_{TX}/P_{Bat}, η_{AntTX} transmitting antenna efficiency P_{Rad}/P_{TX}, η_{Rad} radiation efficiency P_{Inc}/P_{Rad}, η_{AntRX} receiving antenna efficiency P_{RX}/P_{Inc}, and:

$$P_{Noise} = kT \times BW \quad (2)$$

where the channel is assumed to exhibit additive white Gaussian noise, kT is the characteristic energy, and BW the channel bandwidth. Radiation efficiency and therefore incident power P_{Inc} decrease with the square of transmission distance d and signal carrier frequency f_C:

$$\eta_{Rad} = \left(\frac{P_{Inc}}{P_{Rad}} \right) = \left(\frac{c}{4\pi df_C} \right)^2 (1 - |\Gamma|^2)$$

(3)

where " is the reflection coefficient at the transmitting antenna's terminal and c the speed of light. Supply power P_{Bat} consequently increases with BW, SNR, the square of distance d, and the square of carrier frequency f_C and decreases with increasing PA efficiency η_{PA} and transmitting and receiving antenna efficiencies η_{AntTX} and η_{AntRX}:

$$P_{\text{Bat}} = \frac{\text{SNR} \cdot K T \cdot \text{BW}}{\eta_{\text{PA}} \eta_{\text{Ant,TX}} \left(\frac{c}{4\pi d f_c} \right)^2 (1 - |\Gamma|^2) \eta_{\text{Ant,RX}}}$$

(4)

which is why the specification requirements of wireless sensor nodes must be relaxed as much as the application can possibly allow, that is, require the least possible BW, transmission distance, and carrier frequency f_c .

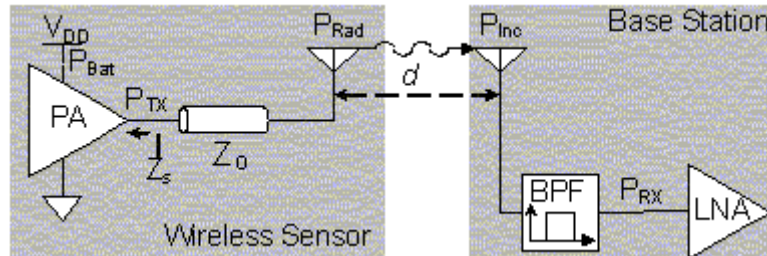


Figure 3. Basic telemetry components and loading environment of a wireless system

The protocol used to [encode](#) and transmit data superimposes various requirements onto the PA and its subsequent efficiency. Emerging [protocol](#) standards like [Bluetooth](#) and Zigbee cater to bandwidth-limited portable applications like cellular phones that require both low power and high bandwidth, while affording the luxury of batteries that can source milli-Watts of power. Wireless sensor nodes, however, powered from micro-power batteries, collect data infrequently and therefore has minimal transmission and [storage](#) requirements, which implies bandwidth often is (and should be, given the space restrictions of the device) low. Simpler, more efficient, and lower bandwidth protocols, such as on-off keying (OOK) or frequency-shift keying (FSK), are better suited (Figure 4 [6]-[7]) because they do not carry any information in the envelope of the signal. The resulting linearity requirements of the PA are relaxed and its circuit [architecture](#) subsequently simplified to more efficient switching topologies (for example, class-D, -E, and -F amplifiers).

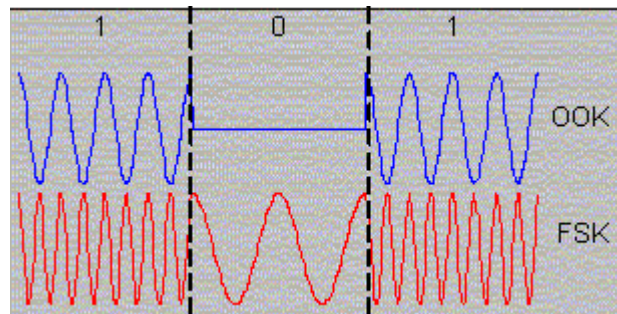


Figure 4. On-off keying (OOK) and frequency-shift keying (FSK) signals for binary word 101

These protocols adopt simple encoding algorithms to transmit "1"s and "0"s. OOK signals, for instance, encode a "1" by the mere presence of a signal and a "0" when no signal exists and FSK signals encode a "1" with a generally high-frequency component and a "0" with the low-frequency counterpart. Between the two, OOK is more power efficient because the amplifier is completely switched off during zero-transmission events. It is also simpler to implement because it does not require the high-power PLLs while the FSK scheme does. OOK, however, is more sensitive to noise because it still depends on signal amplitude, not frequency.

In the end, both energy (e.g., 10 μ W of average power over the expanse of six months to a year) and peak power (for example, 1mW) are scarce in self-powered, micro-scale wireless sensor nodes, and telemetry challenges both. The transmission operation must therefore be limited and duty-cycled. To decrease its peak-power demands, the system should require low signal-to-noise ratio, signal bandwidth, transmission distance (e.g., one to three meters), and carrier frequency (for example, 900MHz). The PA and transmitting and receiving antennas must be as efficient as possible, in spite of the geometry restraints of micro-scale dimensions. Simple, power-efficient, constant-envelope protocol schemes like on-off keying (OOK) are optimal in this regard because they demand lower linearity and consequently impose less power demands on the system.

Practical wireless sensor applications

Low time-constant sensing parameters like temperature and humidity are compatible with the aforementioned low-power telemetry requirements because they need not be sensed continually and their transmission requirements are low. Parametric [compliance](#) checks of equipment and appliances over extended time-cycles are also similarly compatible because metrics like filter integrity, electromagnetic interference sensitivity, and average tire pressure also have slow time constants and can require [bit](#) rates of 10kb/s or less. Monitoring is more feasible than controlling functions, however, because the former only requires one-way transmission and wake-up features while the latter requires considerable bidirectional traffic. Additionally, short-distance telecommunication to less power-constrained portable devices to collect data from the wireless sensor node, similar to what some power companies adopt when checking house meters, and node-to-node ad-hoc-like transmission are preferred over far-away central station communication schemes. Pressure, humidity, and temperature, unlike accelerometers, are simpler and demand less power and are therefore preferred, but like telemetry, their signal-processing electronics are duty-cycled and possibly confined to sub-threshold, low-bandwidth operation. In all, self-powered, wireless sensor network applications may not enjoy the signal traffic and control features consumer portable devices like the cellular phones offer but their non-invasive, self-powered features enable less bandwidth-intensive monitoring functions over the expanse of time and space currently impossible with existing technologies that can enhance system performance of older and emerging technologies at grander scales, which is the driving motivation for this research.

For additional details, questions, and/or comments on this article, please contact us, the Georgia Tech [Analog](#) and Power IC Design Laboratory, at gtap@ece.gatech.edu. More information about our research can be found at <http://www.rincon-mora.com/research>.

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