Sustainable Sensing for a Smarter Planet

At what scale is indoor solar harvesting the better primary power source?

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Over the last decade, tiny, low power, wireless networked sensors ("sensornets") have given visibility and voice to a myriad of physical processes including the dynamics of human social contact networks [6], the response of bridges to external forces [3], and the micro-climate conditions surrounding redwood trees [10], among many others. These sensors have increased our understanding of the world by providing a previously unattainable macroscopic view of human interactions, structural dynamics, and plant eco-physiology. Today, many believe that similar sensor technologies will play a key role in creating a smarter and more sustainable planet by helping us observe human activities, monitor resource consumption, and guide building controls with unprecedented fidelity and scale—ultimately allowing us to better allocate and use scarce resources.

A major question now facing researchers and engineers is how to go about transforming today's relatively small-scale sensornets into tomorrow's large-scale ones that can operate hassle-free, embedded in the environment, for extended periods of time. Researchers are working on many fronts to push the technology forward—reducing system power draw, adapting communication protocols, revisiting operating system design, miniaturizing antennas, designing new radios, creating more stable clocks, developing novel sensor materials, and shrinking batteries to chip-scale packages. However, all of these efforts will be for naught if the devices frequently deplete their energy supply and require human intervention for a recharge or replacement, as most systems do today.

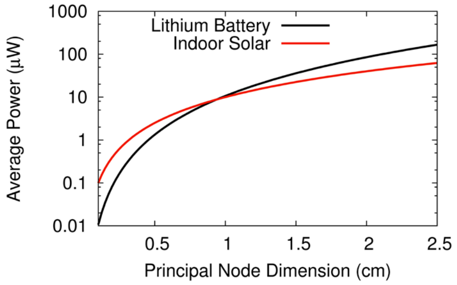
The key to scaling sensors to be deployable broadly and deeply lies in making them sustainable. Today's predominantly battery-powered sensors simply require too much maintenance overhead for us to consider them a viable approach for next-generation sensors. Replacing batteries on just a handful of devices is difficult enough; trying to replace batteries on thousands of sensors embedded in ceilings, walls, floors, and fixtures is untenable. But, even if it were feasible to replace batteries periodically, the resulting e-waste would be unconscionable and antithetical to the very sustainability efforts the sensors are attempting to support. Hence, for wireless sensors to realize their full potential, they will need to break their addiction to batteries and opt instead for a more sustainable power source—energy harvested from their surroundings.

Beyond these qualitative arguments lies an important quantitative one as well: the effect of scaling on energy storage and harvesting. As sensors scale to smaller and smaller dimensions, energy storage capacity diminishes cubically with the principal node dimension since storage requires volume. Solar cell power, in contrast, diminishes quadratically with the principal node dimension, since irradiance falls across an area.

To make the discussion more concrete, consider the question: "At what scale is indoor solar harvesting the better primary power source?" Assume the entire volume (L^3) of a sensor of length L is devoted to energy storage and that volume is occupied by a non-rechargeable Lithium primary cell whose energy density, ρ, is 653 mW-hr/cm^3 and whose useful life, T, is bounded to seven years (due to its shelf-life). The average power the battery could source is $P = \rho L^3/T$. A conservative estimate of the average solar irradiance on an indoor surface, H_d, is 10 μW/cm^2, and the average power is $P = H_d L^2$. Setting these two expressions equal to each other and solving for L gives 1cm as the inflection point where solar (1cm^2) beats batteries (1cm^3) over a seven-year horizon, as **Figure 1** shows.

Of course, this analysis ignores several factors—like the overhead of battery packaging, the inefficiency of solar conversion, and the unrealistic (100%) node volume dedicated to the battery—but the general trend should be clear: batteries are the best option for today's sensors, which often occupy one or more cubic inches. However, batteries become less attractive as node dimensions shrink to centimeter scales and beyond, or as designs become more planar and shed their third dimension. And, at millimeter scale, solar provides a 10x improvement in average power—100nW vs 10nW.

Figure 1. An energy-harvesting reality check. This figure shows how power harvested from indoor solar compares with power drawn from an internal battery. As a cubic sensor's length *L* falls below a centimeter, a solar cell of size L^2 can deliver higher average power than a Lithium battery of size L^3, over a seven-year horizon.



ENERGY SOURCES

Scalable sensing requires sustainable sensors that can operate in near-perpetuity from the energy harvested from the ambient environment, from the phenomena being sensed, or parasitically from a host. An ambient energy-powered sensor might, for example, operate from indoor lighting or the energy in ambient RF signals [7]. A phenomena-powered sensor might harvest the mechanical energy expended during a footstep or involved in pushing a button [4]. And, a parasitically powered sensor might harvest some of the energy flowing to an electrical plug load or the electrical energy delivered over a smartphone's headset port [2].

More broadly, energy could be present in the environment in any of the six primary energy domains including electrical, mechanical, thermal, magnetic, radiant, and chemical:

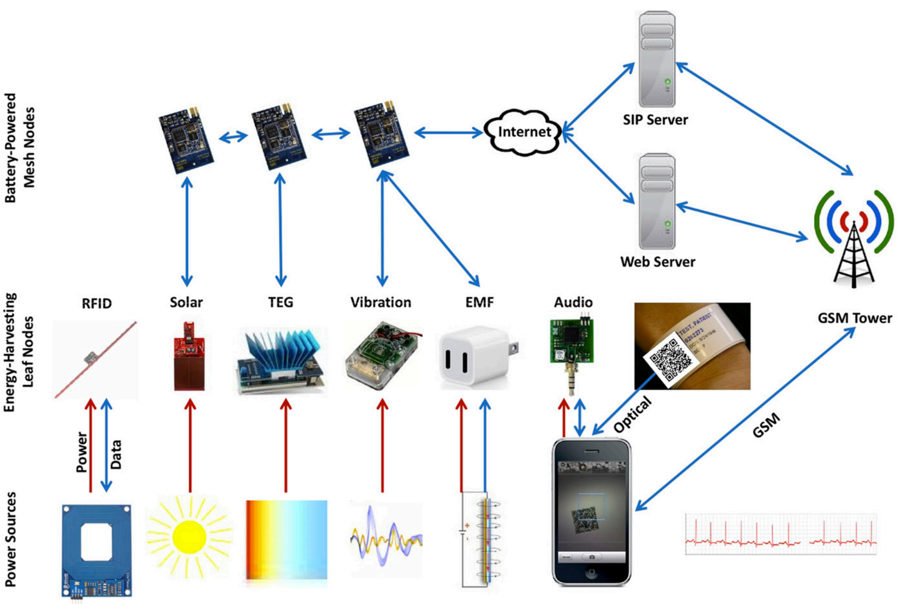
- **Electrical** energy sources include the electric fields that are generated by radio and television stations, mobile phones, wireless access points or power lines, and are "harvested" with antennas.
- **Mechanical** energy sources include door closings, human footsteps, button pushes, tire rotations or appliance vibrations, and are harvested with piezo-electric transducers or through mechanical-magnetic-electric conversion.
- **Thermal** energy sources include temperature differentials between hot and cold water pipes, the indoor and outdoor sides of a window, a kitchen stove, and the ambient air or a server's exhaust and a rack's metal frame. Thermal energy is often harvested using thermoelectric generators.
- **Magnetic** energy sources include the changing fields that emanate from a wire when an AC plug load draws current or when magnet embedded inside a door moves past the frame, and is harvested with electromagnetic induction.
- **Radiant** energy sources include the sun, room lights, miners' headlamps, computer monitors, nuclear radiation, or television screens, and are harvested with photovoltaic cells.
- **Chemical** energy sources include flow batteries or microbial fuel cells (in which bacteria convert wastewater into electricity), and is harvested through electrochemical reactions.

Figure 2 shows how energy sources, energy harvesting sensors, battery-powered sensors, mobile phones, and backend infrastructure will interact in future sensor systems.

In many applications, the instantaneous power available via harvesting is far less than required for operation. In such cases, energy must be buffered until enough has been accumulated to perform some atomic quanta of useful work (for example, taking a sensor reading or transmitting a packet). Energy storage options include capacitors, super capacitors, and rechargeable batteries, with each technology occupying a different point in the space of energy density, power density, voltage profile, leakage, size, and cost. Higher energy densities translate to a smaller size for a given energy storage quanta or a longer lifetime for a given storage volume. Batteries offer the highest storage density, followed by super capacitors, followed by regular capacitors. Higher power densities translate to greater power delivery per unit surface area of the electrodes. In contrast with energy density, capacitors offer higher power density than batteries.

If sensors were unconstrained in either their energy storage or their power draw needs, they could use the technology that best optimized a single objective. Unfortunately, that's not the case—thin film batteries often cannot deliver the peak power required for communications and small capacitors cannot store sufficient energy for long periods of power-free operation. Capacitors also leak much more than thin-film batteries, especially with increasing voltage, so they are ill-suited to long-term energy storage at voltages in the 3–4 volt range. A voltage source that is nominally 3.7V, like a thin-film Lithium ion battery, can be helpful as

Figure 2. A plausible system architecture for combining energy-harvesting leaves with the battery-powered sensornet tree. Leaf nodes will operate from ambient electrical fields (for example, Intel's WISP), radiant sources (for example, Cymbet's Solar Energy Harvester), thermal gradients (MicroPelt's TE-Power PLUS), mechanical vibrations (Adaptive Energy's JouleThief), magnetic fields (Michigan's MpowerCube), and audio headset power (Michigan's HiJack).



a nanopower bias voltage for electronic switches (for example, the FET switches that control the flow of charge between energy producers, buffers, and consumers). As a result of these tradeoffs between batteries and capacitors, many energy-harvesting sensors will incorporate multiple technologies and employ them in complimentary functions. There will also be some energy harvesting sensors that will operate from just a capacitor—perhaps just a few hundred microfarads—in a "fire and forget" manner where a sensor reading and packet transmission is enough to deplete the energy stored in the capacitor.

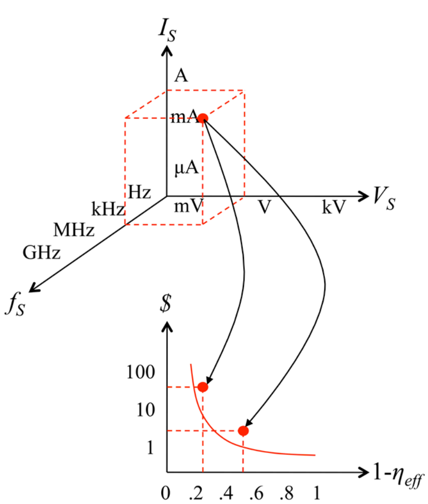
POWER CONVERSION

Energy harvesting systems are often designed around low-output, intermittent power sources. Systems designed to operate in this regime may need to harvest ill-conditioned power across wide-ranging input voltages, currents, and frequencies, supplied from a variety of sources. And, since harvested energy is often in short supply, and the devices that convert radiant, mechanical, thermal, magnetic, or chemical energy into electrical form are relatively large and costly, the power conversion circuitry should be as efficient as possible. Of course, in many applications, the total cost of a sensor, including the power supply, is also constrained. Therefore, the power conversion circuit should also be as inexpensive as possible. Since the power available from many energy harvesters can vary, the source (the harvesting device) and load (the power conversion circuitry) should be impedance-matched to ensure maximum power transfers occurs (that is, the source and load impedances should be complex conjugates). Finally, some sensors may need to cold boot (start from a state of complete depletion) while other sensors may have a longer-term energy reserve, so paying attention to the power converter's startup operation is important.

Different energy sources output markedly different levels of power, and a particular source might occupy just a single point (or small area) in the input space, as **Figure 3** shows. The source voltage might be sub-threshold ($Vs<V_T$), meaning it cannot fully turn on a transistor. The source voltage could also fall between transistor threshold voltage and the circuit operating voltage ($V_T<Vs<Vcc$). Or, the source voltage might be somewhat above the circuit operating voltage (Vs>Vcc) or much greater (Vs>>Vcc). The source might offer a constant output—a DC voltage—or it might have a non-zero frequency—an AC voltage. In the case of an AC source, the frequency could range across a wide swath of values. Some sources might be 60Hz, other sources might be tunable in the 20–20kHz audio band, still other circuits might operate at VHF or UHF television frequencies, while still others might operate at 2.4GHz, but all AC source must be rectified. Similarly, the source current could exhibit a range of values (less than, approximately equal to, or greater than the average load current).The key point is that the design space of possible inputs is vast and consists of many points.

The power supply engineering challenge rests in efficiently and inexpensively converting the input source into a stable output voltage that can power the sensor electronics. When the power is plentiful (that is, more than enough to operate the circuit) and the input voltage is greater than 1V (AC or DC) and less than about 16V (AC or DC), the designer has many off-the-shelf choices, as many conventional switching

Figure 3. The input power source could span orders of magnitude across voltage, current, and frequency, resulting in a vast space of possible designs to convert the power into more usable form (for example, 3VDC).



regulators will suffice. However, when the voltage falls below about 600mV (or 300mV in some cases) or exceeds about 50V, and the source power (and/or current) is lower than the sensor requires, the design space becomes more challenging. To illustrate some of the difficulties, consider the following two design points:

Ultralow Voltage DC. A thermoelectric generator-operated sensor might need to run from just tens of millivolts. The main challenge with such ultralow voltages is that they cannot easily switch transistors. Swanson and Meindl showed in 1972 that the minimum usable supply voltage for CMOS inverters is given by $8kT/q$, where k is the Boltzmann constant, T is the absolute temperature, and q is the charge of an electron [9]. The minimum voltage is about 200mV, and we see some switching regulators capable of operating near this level. Operating below this input voltage level requires more novel approaches. One such approach is to use a micro transformer to boost the voltage to a higher level (and then use the boosted voltage to switch off, or disconnect, the primary to create an inductive kick), but in order for this approach to work, the supply must provide a sufficiently fast ramp up. A slow ramp up—as might be the case with a solar cell slowly increasing its output current with a rising sun or a thermoelectric generator increasing its output slowly as water temperature slowly rises—may not provide the needed voltage on the transformer secondary to kick-start the circuit.

High-Voltage AC. A cubic-inch AC power meter might operate from the same (high) line voltage it measures. The main challenge with high-voltage AC lies in efficiently and compactly reducing it to the low-voltage DC suitable for powering electronics. Conventional AC-to-DC power converters use bulky 60Hz transformers, which provide isolation, but limit miniaturization and efficiency. The basic issue is that at low frequencies, a miniature transformer's core saturates and it cannot efficiently store or transfer energy from the primary to the secondary. This, however, is not a problem at higher frequencies. Transformers that are just a few millimeters on a side are efficient in the 10kHz range and on-chip transformers have exhibited high efficiencies in the 300MHz range.

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Other AC-to-DC power supply designs drop the high voltage over a capacitor and regulate the output using a Zener diode. This design (called "shunt capacitor-fed") requires the capacitor to withstand high-voltage transients and be sized proportionately with the load current, making it too large for some designs. Furthermore, the use of the capacitor results in non-unity power factors and use of the Zener diode leads to inefficient regulation. Some newer designs (called "switched shunt-capacitor") replace the Zener diode with a FET switch whose operation is precisely timed, improving efficiency, but not size. Other designs eliminate the series shunt capacitor and instead use a bridge rectifier followed by a high-voltage reservoir capacitor (which does not have to be rated to handle line transients, so it can be smaller). However, the capacitor must have a high-voltage rating, which increases size. And still other approaches switch a high-voltage transistor that directly charges an output capacitor. The sudden switching, however, creates considerable noise and results in a bursty load profile with a low, non-unity harmonic power factor. The key point is that even when ample power is available, converting it into a more usable form can present many challenges and trade-offs, even for a single point in the design space.

IMPLICATIONS ON SYSTEM SOFTWARE

Today, most software systems take the presence of reliable power for granted. Imagine how different and difficult programming would be if operating spans were very short and power could disappear with little or no warning? In that world, computers might need to boot very quickly and save their state with predictable energy and latency. Power hazards would need to be exposed to the operating system scheduler and treated like any other scarce resource. Sensing, computing, communications, and storage would be modulated by the available energy, and the timeliness of operations would become unpredictable and subject to externalities.

Power-disruption-tolerant programming is fraught with many difficulties. If power could truly disappear at any moment, then a sensor would have to periodically checkpoint its state to stable storage. However, check pointing is itself a time- and energy-intensive operation, and doing it too frequently only serves to exacerbate the very situation the system hopes to avoid. One way to balance checkpoint frequency and energy reserves is to expose the energy state and non-volatile memory access costs to the systems scheduler. With a better model of the costs, and an awareness of state, the scheduler can make better decisions on checkpoint times, saving energy but ensuring state preservation during power outages.

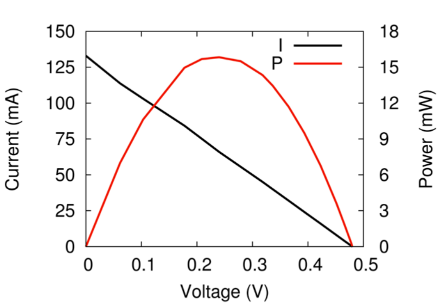
Neighbor discovery and rendezvous present major challenges for energy-constrained, intermittently-powered sensors. As sensors scale to smaller geometries, their antennas must necessarily scale as well. This implies that antenna resonance will occur at higher frequencies, in turn leading to shorter communications range and higher energy per bit. And, since in many cases, sensors may not be located within radio range of wall-powered neighbors, energy-constrained neighbors will need to discover each other. However, with very limited energy and power density, sensors will not be able to communicate often, so it remains an open problem how nodes will discovery each other for the very first time, and then continue to maintain connectivity in the face of power disruptions. The challenge is particularly acute if a device's sense of time might be lost without external power. In such scenarios, sensors would lose track of their neighbors' awake times, making it especially difficult to rejoin an already existing network.

A CONCRETE DESIGN POINT

As a concrete design point to illustrate the trade-offs and challenges, consider the seemingly simple problem of powering a sensor from the iPhone's headset port. Why would anyone want to do such a thing? One reason is that the mobile phone is the most pervasive computing, communications, storage, and interaction device in the world and the headset port is among the most common interfaces. A headset-powered sensor opens up the iPhone (and other smartphones) to a world of inexpensive, plug-and-play of peripherals like personal credit card readers [8], pocket television remotes [5], or a myriad of other mobile peripheral (for example, inexpensive EKG monitors) [1]. Although not "traditional" energy harvesting, this genre of phone peripherals illustrates many of the basic issues that designers face in a fun and relevant context.

The first question a designer faces with any energy harvesting system is, "How much power is available from the source?" To answer this question in the context of the iPhone's headset, one could use software like Faber Acoustical's iPhone SignalScope Pro to generate a range of audio waveforms of various frequencies (from 20Hz to 24kHz), output them over the audio port, and measure the resulting current and voltage across a set of reference loads. The results of this experiment are shown in **Figure 4**. As the load is varied from 0 to 15 kΩ, the output voltage and load current are measured at several points. A linear fit of the data yields the (essentially linear) I-V curve and provides the answer to first question. The maximum power transfer occurs at 240 mV_{rms}, when delivering 66.0 mA_{rms}, for 3.6Ω load impedance.

Figure 4. Available power from the iPhone headset jack. This data shows that it is possible to draw 15.8mW from an ideally matched load of 3.6 Ω, which is enough to power many low-power electronics. To be useful, however, the power must be rectified from AC to DC, boosted to a few volts, and filtered.



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Design Alternatives. The next question a designer faces is how the available power should be converted and buffered at low cost? The two engineering challenges that lie in making the headset power more usable are: increasing the signal amplitude, and rectifying the AC signal into a DC one. **Figure 4** shows that the open circuit voltage, Voc, is less than 500mV and that the maximum power point voltage, Vmpp, occurs at 240mV (for a maximum output of 15.8mW). These voltages are far below the turn on voltages of switching regulators (typically in the range of 800mV to 900mV). They are also below the required startup voltage, after rectification, of ultra-low voltage step-up DC-DC converters, like the Seiko S-882Z, which require 300mV to start.

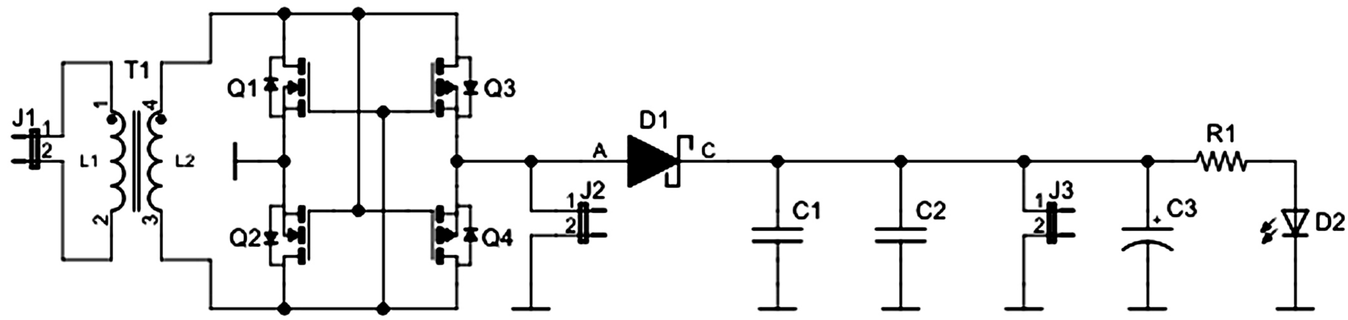
Rectification losses can be significant in both high-power and low-voltage systems. In our case, for example, to achieve maximum power transfer, an RMS current of 66mA is required. When rectified using even a low-loss Schottky diode like the DFLS120L, a 200mV forward voltage drop occurs, meaning that 80% of the power is lost during rectification, and only 20% can be delivered to the load. Of course, this assumes that only a single rectifier diode is on the path, which would of course reduce the available power by 50%. If two diodes are on the path, as would be the case for a bridge rectifier, the losses would be even higher. These kinds of losses present major challenges in both low-voltage and high-current designs.

Synchronous rectification is one approach used to reduce these losses. The basic idea involves replacing the diodes in a bridge rectifier with actively controlled FET switches. The FETs are turned on (by strongly driving their gate) whenever a positive potential exists the FET's built-in body diode is used instead of a diode. In low-voltage applications like ours, the problem is generating a sufficiently high gate drive voltage to turn on the FET switch. Given the low voltages involved, this would require many stages of (inefficient) voltage multiplication ladders.

We end this exploration of design alternatives by eliminating two simple, but ultimately unworkable, options: harvesting DC directly from the audio output and harvesting DC from the microphone bias voltage. The first option, directly harvesting a DC voltage, does not work with most phones, including the iPhone, because the earphone signal path is effectively AC-coupled, and therefore blocks DC. This eliminates the possibility of simply generating a DC output voltage to power the external devices. Using the microphone bias voltage is also difficult for a sensor application since the microphone line is used as the data input channel to the phone, which is modulated externally. The microphone bias signal is also capable of supplying far less power than the audio output (that is, 0.85mWvs 15.8mW), so its utility as the sole power source is pretty low.

In the broader context, when designing energy harvesting and power conversion systems, one often has to completely rethink the ways in which energy is obtained, converted, buffered, and used. In this case, we ruled out the two most obvious approaches to converting AC power—a diode/

Figure 5. An energy "harvesting" circuit. A 1:20 microtransformer boosts the input voltage. A FET bridge efficiently rectifies the AC signal to DC. Parallel Schottky diodes provide low-loss blocking to prevent the output filter capacitor from discharging through the FET bridge. An LED with current-limiting resistor provides a visual power indicator.



bridge rectifier and a synchronous rectifier.

HiJack Energy Harvester. To sidestep the first basic challenge—low-supply voltage—HiJack uses a step-up microtransformer. The stepped-voltage is then passed through a FET bridge for rectification, addressing the second basic challenge. Since the stepped-up voltage is substantially higher than the FET threshold voltage, the FETs are in conduction and offer low loss. Another benefit to stepping-up the voltage is the diode forward voltage drop represents a small fraction of the rectified voltage, substantially reducing diode losses (see **Figure 5**).

A third basic challenge lies in matching the load and source impedances to achieving high-efficiency power transfer from a source to a load. In this case, the impedance offered by the microtransformer's primary winding should be matched to the iPhone's audio output port's impedance of 3.6 Ω. This condition occurs when the transformer is excited with a 22.9kHz tone, given the transformer's 25μH primary inductance. The target excitation frequency sits just at the edge of the audio band, and therefore just at the edge of what the iPhone is capable of producing. Fortunately, however, we have complete control over the excitation frequency within the audio band, so we can generate a 22kHz waveform, which achieves near optimal power transfer to the HiJack energy harvester circuit. However, this isn't always the case, so designers often find themselves designing a circuit to match the source frequency (for example, 60Hz AC, 700MHz TV, or 2.4GHz WiFi).

To illustrate the circuit's operation, we implemented the entire system, as shown in **Figure 6**. The circuit requires a footprint of 1.0" x 0.35" (although a full 1" x 1" by board with other components is shown). **Figure 7** shows a trace of the circuit in operation. The iPhone generates 22kHz, 500mV peak-to-peak square waves that is low-pass filtered. The RMS value of the signal is 207mV, meaning that approximately 15mW is delivered by the phone, or about 90% of peak power. Channel 1 (orange) shows this filtered audio output signal. Channel 2 (blue) shows a peak 4.24V signal after rectification using the FET bridge. Channel 3 (magenta) shows the output after passing the rectified signal through the blocking diode, which drops 230mV at peak current, providing at worst 94.5% efficiency. Channel 4 (green) shows the voltage across an LED after the signal passes through a 699Ω high-side current-limiting resistor, demonstrating the operation of a complete energy harvesting system.

CONCLUSION

This article started with the claim that scalable sensing requires sustainable sensors and described many of the

Figure 6. A complete HiJack device with the energy harvesting circuit combined with a microcontroller and molded into an iPhone headset-pluggable package.

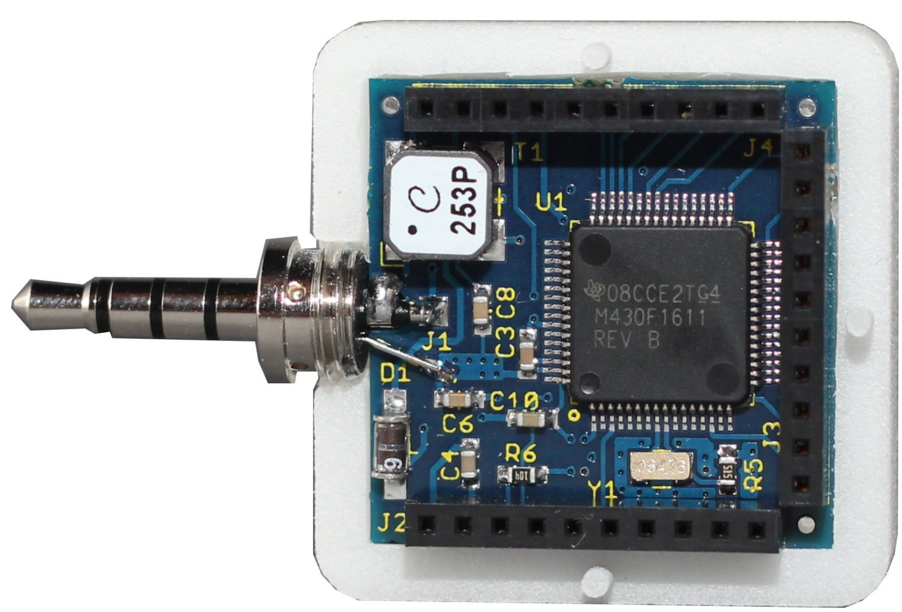
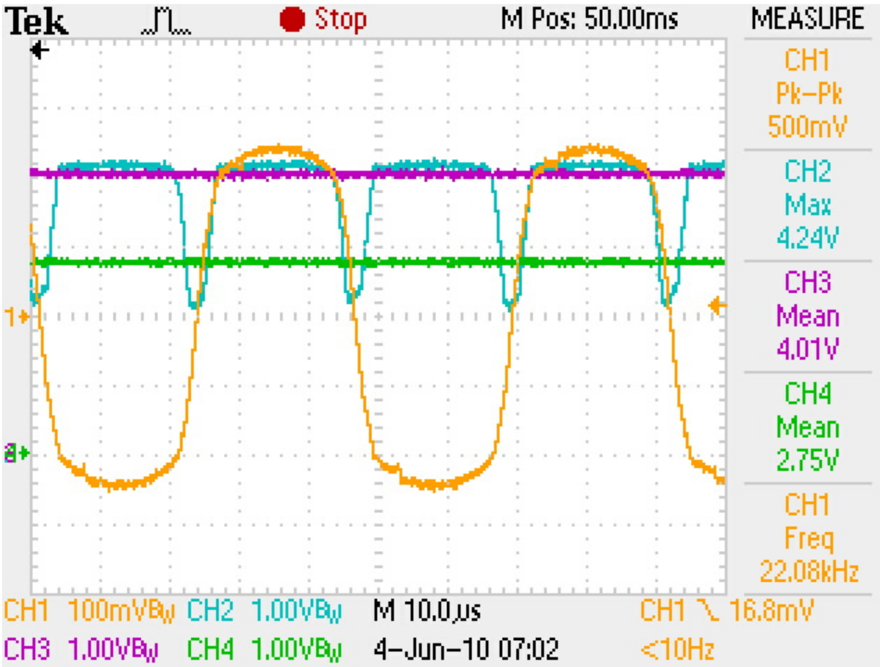


Figure 7. Operation of the HiJack energy harvester circuit. Channel 1 (orange) shows the filtered audio excitation signal. Channel 2 (blue) shows the signal after rectification. Channel 3 (magenta) shows the output after passing through a blocking diode which drops. Channel 4 (green) shows the voltage across the LED.



technical challenges and trade-offs in designing energy harvesting sensors. We argued that it should soon be possible to construct near-nanopower networked sensing systems at the centimeter or millimeter scale, and that these systems could advance macro sustainability efforts. It turns out that this relationship is really a two way street—a concrete set of application drivers, coupled with realistic constraints, pushes the underlying technology to new heights.

Called to action in the service of sustainability, energy-harvesting sensors will pull from many areas of science and engineering—circuits, chemistry, materials, mechanics, MEMS, power electronics, VLSI, and wireless among them—and push forward many aspects of sensornet works—system architecture, near-nanopower operation, system startup, time synchronization, environmentally driven synchronization, power-disruption tolerant programming, and energy management.

Many of the basic building blocks for energy harvesting—miniature solar cells, piezo-electric harvesters, thermoelectric generators, surface-mountable thin-film batteries, and energy harvesting ICs—have started transitioning from research to industry. Companies like AdaptiveEnergy, Advanced Linear Devices, Clare/IXYS, Cymbet, EnOcean, Linear Technology, MicroPelt, MIDE, and PowerCast are among some of the suppliers in this space. The emergence of a global ecosystem port ends a dramatic shift in both how we power future devices and how deeply and densely they might be deployed in the world. The challenge before us now lies in combining these various technologies and components into reliable, predictable, and functional systems.

If we are successful, then the resulting technology could support broader sustainability and eco-science efforts as well. For example, the flow of water through a watershed could be better understood: how much falls as rain, how much is absorbed by the ground and trees, how much is removed through evapotranspiration, and how much drain via creeks and rivers? Or the effect of temperature on animal habits and habitats could be studied: how do foraging, feeding, sleeping, and hibernating activities change with changes in the climate? These and other questions are of great importance to science and society.

Biography

Prabal Dutta (prabal@eecs.umich.edu) is an assistant professor in the Electrical Engineering and Computer Science Department at the University of Michigan. His research interests include wireless, networked, and embedded systems, and their applications to societal-scale challenges. He holds a Ph.D. in computer science from the University of California, Berkeley and is a member of the ACM, IEEE, and Usenix.

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