Perpetual Sensing for the Built Environment

An energy harvesting sensor system architecture emerges through multiple generations of sensor development and deployment for smart building applications.

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Pervasive sensing and computing technology will play a key role in future buildings. In the US, for example, federal sustainability goals mandate that 50 percent of commercial buildings must become net-zero energy by 2050. To realize this goal, existing buildings will require a wide range of retrofits and improvements. However, to benchmark buildings and verify the intended effects of the improvements, many critical building parameters, including electricity, gas, and water usage, must be sensed and analyzed both before and after the improvements are made.[1]

Furthermore, many of the improvements themselves—such as advanced daylight harvesting, where indoor lighting is adjusted in a fine-grained manner in response to outdoor solar irradiance and the degree of shading—require their own sensors that can monitor occupancy, light level, glare, and shade setting. However, most sensors installed on walls, work surfaces, ceilings, shades, and many other places can't be plugged into mains power, and users won't tolerate frequent battery replacement. This suggests that a different and more scalable sensing paradigm is required. Motivated by these emerging applications and our own difficulties in fielding long-lived indoor sensors at modest scale, we decided to explore the factors preventing broader adoption of pervasive sensing and computing within buildings.

Scaling Challenges

Contrary to conventional wisdom, we found that low-power mesh networking wasn't as critical in many indoor settings as once believed. With wall-to-wall Wi-Fi and copious Ethernet ports available in many places, it's now possible to place inexpensive, mains-powered gateways within one hop of most sensors. Furthermore, if neither of those options is viable, then cellular connectivity is an increasingly viable gateway connectivity option.

An equal or even greater challenge in commercial spaces occupied by people centers on aesthetics and cost. To be viable, sensors must be small and sleek, and their total cost of ownership can't be very high. Today, unfortunately, most sensors aren't designed with these factors in mind. Take, for example, plug-load power meters. Most are large, unattractive devices that many are unwilling to deploy pervasively. The key to scaling down their size is often tied to reducing their power draw, because the size of the energy storage component often dominates the volume. With mobile and wearable

market forces driving down sensor cost and power, continued scaling in size is now possible.

As sensor size and cost continue to decline, installation and maintenance costs begin to dominate the total cost of ownership. The main cost driver is often provisioning for power, whether at installation time or on an ongoing basis. Consider circuit-level meters inside of electrical panel boxes. Typically, dozens of current measurement transducers (called *current transformers*) are placed near circuit breakers, and their leads are routed to electronics located elsewhere. The electronics have a large footprint and high power draw in part because they are centralized. Unfortunately, accommodating the electronics and their power supply usually requires upgrading or augmenting the panel box—a costly proposition. However, as sensor component size, cost, and power continue to fall, it becomes possible to integrate all the electronics into the transducer itself and perpetually power it from the minute levels of energy harvested from current flow, eliminating the bulk of installation and maintenance costs.

Small, inexpensive, and perpetually powered sensors offer an attractive paradigm for pervasive sensing and computing.[2] However, simply replacing conventional power supplies—such as batteries or mains power—with energy harvesting ones presents many challenges. Harvested energy—from sources as diverse as light, heat, electricity, magnetism, or vibration—is intermittent and variable. To mask this uncertainty and the system challenges that it presents, most energy harvesting systems dramatically overprovision the energy harvesting transducer (solar cells, for example) and energy storage (capacitors, for example), once again driving up sensor size and cost, thus limiting adoption.

Perpetual Sensing

Rather than attempting to mask the inherent intermittency and unpredictabil-

ity in harvested energy, our work has sought to embrace it. The key insight is that the transfer and use of energy usually emits energy, often in a different domain, and that this emitted energy can sometimes be enough to intermittently power simple energy harvesting sensors whose activation rate is proportional to the energy being transferred or used. Consequently, the sensors' mere activation rate signals the underlying energy use. Motivated by the Portuguese word for water hammer, we call this the *Monjolo approach* and define it as follows:[3]

> *The transfer and use of energy usually emits energy, often in a different domain, and this emitted energy is often enough to intermittently power simple, energy harvesting sensors whose activation rate is proportional to the energy being transferred or used, enabling simple sensors.*

When applying the Monjolo approach, the energy harvester becomes the sensor. This approach works well for many things we want to sense in buildings. For example, built-in lighting is difficult to directly meter, but it's easy to harvest energy from the light itself, whose brightness is proportional to the power it draws. Of course, many things we want to sense do not exhibit this power-proportionality property; however, they might still provide some energy, like a door opening, which can trigger activity that causes energy harvested using some other domain to be used. In other cases, we can indirectly detect activity—for example, in motion-activated lighting, harvesting light energy to operate a sensor lets us indirectly monitor occupancy.

Here, we explore these and several other perpetual sensors built using the Monjolo approach. We also explore extensions of these systems to address scenarios it does not support, and consider other sensors that were motivated by the shortcomings of the Monjolo approach

but do not use it for accuracy reasons. (Note that in the latter two cases, the energy harvester is not the sensor.) Figure 1 shows many modular components in our perpetual sensing ecosystem.

Catch Some Rays

Perhaps the simplest Monjolo sensor is the one that harvests indoor light energy, letting us correlate a lamp's power draw with the light it casts. However, building a viable device from off-the-shelf components—a device that's small, sleek, and inexpensive—is more difficult than one might anticipate. Typical indoor irradiance levels fall in the 10–100 $\mu W/cm^2$ range, and after photovoltaic conversion and power supply inefficiencies, perhaps only 10 to 20 percent of that is available for use.

Consequently, one challenge with centimeter-scale indoor sensors is that the idle power of many components, such as processors and radios, can exceed the paltry levels of harvestable power. So, in many cases, the electronics must be disconnected or power cycled constantly. During each power cycle, or *activation*, the device cold boots, initializes the hardware, wirelessly transmits a packet, ensures that a fixed energy quanta is consumed, and powers down. This reduces the idle power but introduces a new challenge—the energy cost of cold booting.

Because a Monjolo sensor cold boots during each activation, energy spent initializing the system reduces the rate of activations and thus the sensor's temporal fidelity. Moreover, embedded bootloaders and operating systems seldom optimize startup time or energy. For example, the default TinyOS distribution requires 237 ms and consumes 2.174 mJ from power-on to packet transmission on the Epic Core,[4] leading to tens of minutes between activations. To reduce startup time and energy, we use an internal oscillator that starts quickly but has poor frequency tolerance to initialize hardware components, employ interrupt or polling rather than conservative timeouts to minimize wait times, run
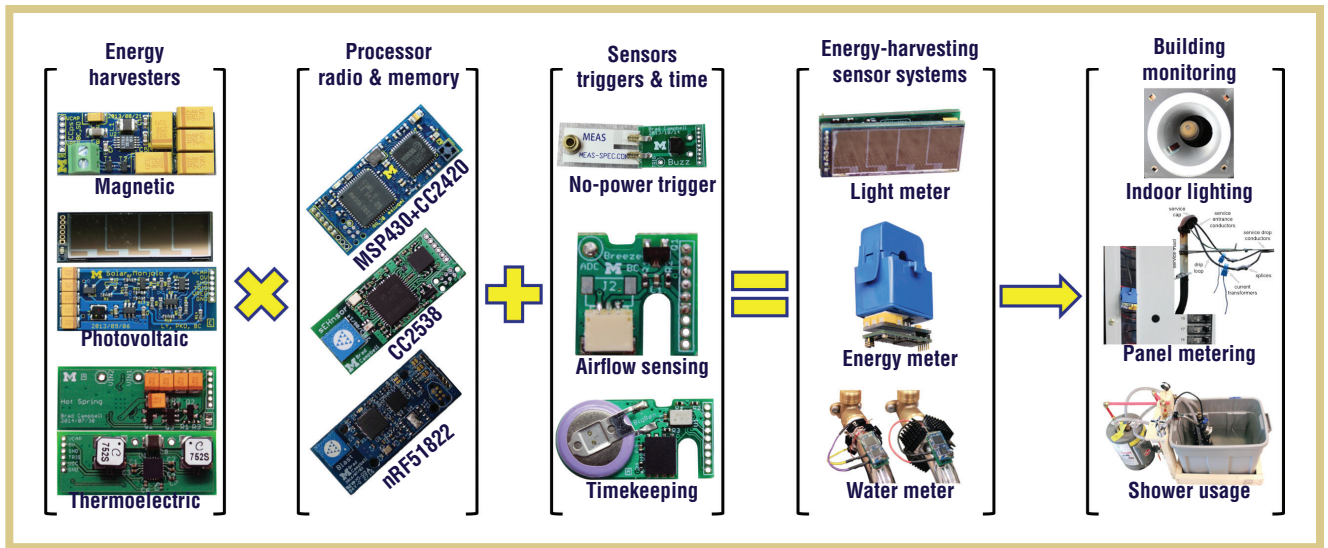
Figure 1. Modular components in the Monjolo ecosystem, including energy harvesting power supplies, processor/radio modules, and various sensors and triggers that are combined to create sensors for building monitoring systems for lighting, electricity, and shower use.

oscillators at the maximum frequency when initializing memory, collapse the radio stack, and parallelize radio startup and memory initialization. Collectively, these optimizations result in startup figures of 3.4 ms and 149 µJ—a 69-times improvement in time and a 14-times improvement in energy. This means that even in poorly illuminated settings, sensors will report approximately once every minute or two, and more frequently in better lit settings or when placed closer to lighting, as would be the case when monitoring them.[5]

Thus far, we have assumed that when a Monjolo sensor transmits a packet, an always-on radio receiver is within reception range to receive the packet. This might often be the case, but there are times when it might be desirable or necessary to transmit data to a battery-powered, duty-cycled radio. In such cases, transmitting a packet as soon as sufficient energy has been harvested will result in lost data.

To address this problem, we can decouple activation from radio transmission, note activation time and count, and transmit this data according to a particular schedule. To initially synchronize communications, we use a variant of Disco, an asynchronous neighbor discovery protocol, in asymmetric mode.[6]

In our design, Monjolo nodes are augmented with an ultralow-power real-time clock that triggers 5-ms duration transmissions every minute whenever sufficient energy is available. Battery-powered nodes listen for 5 ms every 245 ms, ensuring overlapping transmit and receive windows, with a worst-case latency of 50 minutes in the absence of communication failures. This requires a roughly 2.45 percent duty cycle for the battery-powered sensor—an acceptable figure in many cases. Once synchronized, tracking each Monjolo's subsequent transmissions requires just 0.06 percent per node.

Once we decouple system activation from radio transmission—that is, where the activation rate alone doesn't convey all information in the packet transmission interval—it becomes possible to convey additional sensor data. When a device activates, it can sample real sensors, such as temperature and humidity sensors, and include their data in its transmissions. This lets us naturally extend a Monjolo sensor for one domain to support additional sensing modalities.

However, when operating in this regime, it is useful for system software to have finer-grained control over power supply operation. For example, software might want to initiate an early shutdown to conserve energy rather than consume a fixed energy quantum during each activation cycle. This requires a richer power supply control interface than is typically found on sensors, exposing keep-alive, shutdown, and trigger controls. Reexamining the power supply interface can enable other operating modes as well.

Once the power supply exposes a trigger input, an external event can power up a sensor. One example where this is useful is in detecting door-open events. In this application, a zero-power, piezoelectric cantilever triggers a photovoltaic harvester and radio whenever a door opens, resulting in a packet transmission. We designed a sensor, called Buzz, to explore this design point (see Figure 2). Our results show that Buzz detects most door events, but that it also has two predictable failure modes. One type of failure occurs when a room has been dark for a while. Any charge harvested before the darkness leaks away over time, rendering the device unable to activate during the next event. Another type of failure occurs when two or more door events occur in rapid succession. In that case, the harvester does not have enough time to recharge before the second and later events.
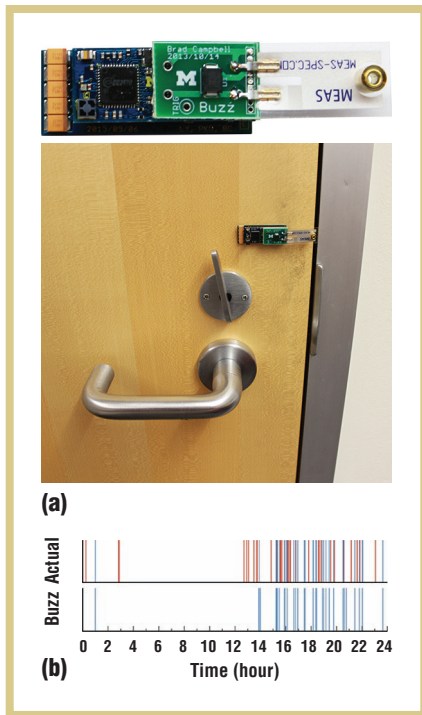
Figure 2. The Buzz sensor. (a) Buzz monitors door events using a piezoelectric cantilever to provide a zero-power trigger when the door moves. If the harvester has accumulated enough charge, the sensor activates and wirelessly transmits a packet. (b) Buzz detects most door events, but some are missed when they occur in quick succession or in the dark.

Both Buzz failure modes occur because the sensors store just enough energy to activate and transmit a packet exactly once. This is an intentional design decision—capacitors that can store enough energy for activation are relatively large and costly and thus not overprovisioned. Increasing the storage voltage on capacitors only hastens their self-discharge rate. Also, at centimeter scales, rechargeable batteries have cycle-life limitations, while both rechargeable batteries and supercapacitors have limits on their instantaneous supply current that are below the peak current required to transmit a radio message. In the future, more sophisticated power supplies could use a hierarchy of storage technologies with intelligent transfers between the elements to address Buzz's failure modes.

Another design point, called Breeze, decouples power from sensing, both physically and logically (see Figure 3). Physically, a photovoltaic panel is placed near a ceiling light (see Figure 4), an airflow sensor is placed on an HVAC vent, and a short cable connects the two. Logically, rather than encoding information about the harvester's activation rate in the radio transmissions, the transmitted data is about the airflow. Unlike traditional sensors, the sample rate is proportional to the brightness of nearby lighting. Although this might seem unusual, it is worth noting that occupancy and lighting are often correlated, and occupancy and demand ventilation are also correlated. So in most cases, Breeze will be able to operate when people are present. However, it may be desirable to augment Breeze with additional energy storage capacity to provide measurements during dark times as well.

So, while light-activated Monjolo sensors are useful on their own, enabling them to connect with battery-powered sensors is possible once they can keep time. Also, decoupling system activation from radio transmission allows additional sensors to piggyback on the Monjolo design, while a rich power supply interface enables new modes of triggered operation.

Current Inductions

Electricity metering is a natural fit for Monjolo-style sensors for both circuit-level and plug-load scenarios. The basic idea is that a time-varying current flow causes a time-varying magnetic field around a conductor, and then that magnetic field can be used to induce a voltage in a coil of wire wound around a ferromagnetic core surrounding the conductor. If the inducted voltage is rectified, filtered, and stored, it can periodically activate a sensor once enough charge has accumulated. Moreover, the sensor's activation rate is proportional to the magnitude of the current flow in the original conductor, provided that a fixed energy quanta is consumed per activation (see Figure 5).
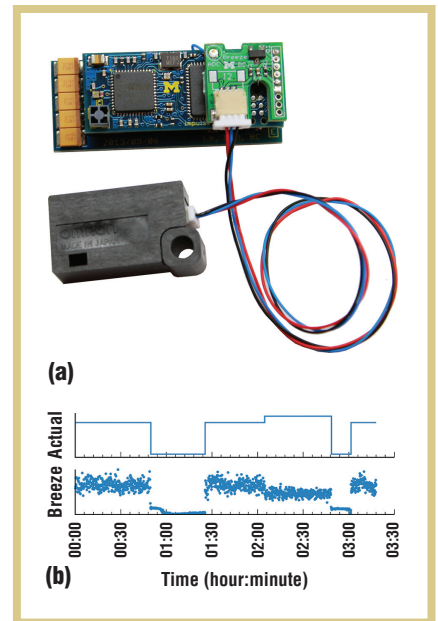

Figure 3. Breeze monitors airflow from a vent. (a) Breeze decouples power from sensing—the photovoltaic panel is placed near a ceiling light, and the flow sensor is placed on the vent. Whenever the system has accumulated enough energy, it boots to take a sample and transmit the data. (b) Breeze detects airflow, but the sample rate is related to the brightness of nearby lights.

One benefit of Monjolo electricity meters is that they draw nearly zero power, but they do have some drawbacks. We have implemented both circuit-level and plug-load meters following this approach and discovered that they work well for resistive loads but exhibit expected errors for reactive (motors, for example) and switching (power supplies, for example) loads because Monjolo meters do not sample the voltage waveform.

Electricity meters in the Monjolo style exhibit a wide range of activation rates in response to monitored load currents. At high load currents, this power-activity proportionality leads to frequent transmissions and potential radio channel contention. To reduce possible contention, we rate-limit Monjolo radio transmissions to no more than one packet per unit time.
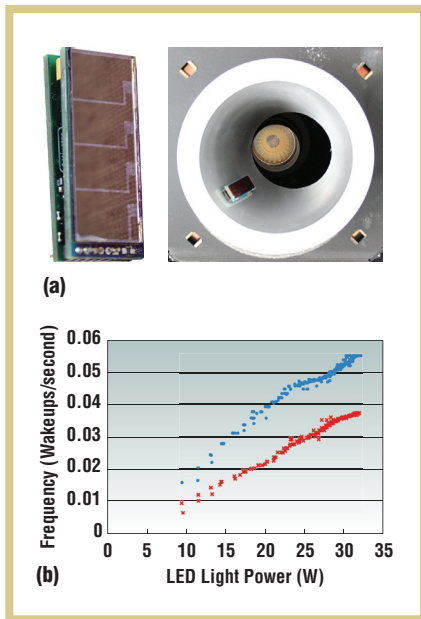
Figure 4. To harvest energy from indoor lighting, this sensor uses an indoor photovoltaic cell. (a) The photovoltaic panel is small enough to fit unobtrusively in a light fixture. (b) As the light's power draw increases, shown in blue, so does its brightness and the activation rate of the Monjolo sensor, shown in red.

However, the challenge in rate limiting lies in measuring the passage of time on a device that loses power between activations. We employ a "countdown timer" implemented using a simple resistor-capacitor (RC) decay circuit. Whenever a packet is transmitted, the capacitor is charged. Thereafter, the capacitor is discharged through the resistor. On subsequent activations, the capacitor voltage is checked to see if it has fallen below a threshold. If it has, a packet is again transmitted and the capacitor is recharged. If the capacitor voltage has not fallen below the threshold, a packet is not transmitted. This ensures that the packet transmission rate is limited, albeit using a "timer" with very poor tolerance and high temperature sensitivity.

By rate-limiting radio transmissions, the interpacket interval no longer conveys the activation rate, because system activation and packet transmission are decoupled. We address this new problem by incrementing a nonvolatile counter on each activation and including the counter value in the transmitted packet. The key to this scheme is a new nonvolatile memory technology called *ferro-electric RAM* (FRAM), which allows low-energy, in-place atomic updates at wire speeds. We use either an external FRAM chip or a FRAM-equipped microcontroller. We avoid conventional EEPROM and Flash technologies because they are poorly suited to Monjolo style sensors due to their high in-place update costs. Logging style updates with EEPROM and Flash are also undesirable because they can't ensure a predictable energy cost for log management operations.

Applying these new techniques, we can implement Monjolo electricity meters that work reasonably well for resistive loads in circuit-level and plug-load configurations. Also, although not appropriate for revenue-grade metering applications, Monjolo electricity meters offer approximate the breakdown of electricity use in homes and offices. This is often enough to identify the major and minor loads, along with their contributions to the total electricity usage, with much higher fidelity than nonintrusive load monitoring.[7] With no need to provision power, they are also easy to deploy and use. Monjolo teaches us that embracing energy harvesting greatly aids in improving utility, but if we desire greater accuracy, we must explore designs that depart from Monjolo's operating approach.

Circuit-level metering. To accurately measure electrical power, both the voltage and current signals must be sampled, and those voltage and current samples must be multiplied, point by synchronized point, to yield power—something that neither Monjolo sensors nor many other sensors do. The main difficulty lies in the fact that for circuit-level metering, the voltage and current signals are physically separated. This is one reason that circuit-level metering systems use centralized electronics and remote current and voltage signal acquisition, typically
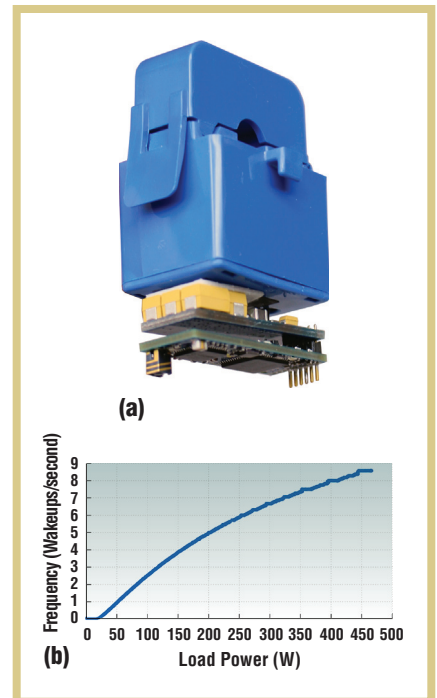
Figure 5. An electricity sensor based on the Monjolo approach. (a) A current transformer, normally used to measure an AC current flow in a wire, becomes a Monjolo current harvester. A split-core model allows circuit panel installation with no downtime. (b) If the measured load exceeds a minimum startup threshold, the sensor's activation is proportional to load power.

with a wired current transformer and long voltage leads. Other designs acquire voltage in one location and current in another, compute the average of each signal, and multiply the average values.[8] While popular, this approach yields apparent, but not real and reactive, power.

Our Gemini design starts with the Monjolo design but improves on it to accurately compute true power.[9] Gemini addresses the drawbacks of prior approaches by decoupling and distributing the voltage and current measurement acquisitions, and recombining them using a low-bandwidth, time-synchronized, wireless channel to offer noninvasive real, reactive, and apparent power metering. Battery maintenance is eliminated using an energy harvesting design that enables the meter to power
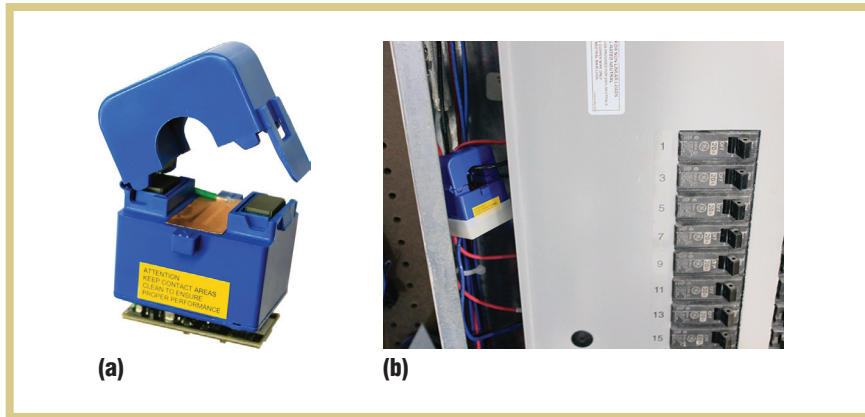
Figure 6. Triumvi is a circuit-level power meter that clips around the wire running to a circuit breaker inside an electrical panel box. (a) It is a noncontact, standalone meter that can be (b) quickly and easily installed in an electrical panel box without requiring any modifications to the panel.

itself from the current transformer. Accuracy is substantially improved over other noninvasive meters by virtualizing the voltage channel. This is accomplished by creating a synthesized voltage waveform with microsecond-level phase matching—effectively letting the meter calculate power as if it could directly measure voltage.

Collectively, these improvements result in a new meter design point that can measure resistive loads with 0.6 W average error and reactive and switching loads with 2.2 W average error—matching commercial, mains-powered solutions. Gemini draws on two complementary research themes—virtual sensors and energy harvesting power supplies—bringing them together to yield a novel design point in the metering space that provides accurate readings every few seconds for loads exceeding 100 W.

Although Gemini offers clip-on installation, energy harvesting operation, and accurate power metering, it does have one major drawback: it requires a nearby, wirelessly accessible voltage monitor that can respond with instantaneous voltage parameters with milliseconds delay and microsecond phase synchronization. This reliance on a wireless link affects reliability, so we began to explore how we could avoid such a fragile design while retaining the benefits of the Gemini approach. One promising idea

we discovered in the literature was to sense voltage in a noncontact manner.[10] The basic idea is that the time-varying potential difference that exists between the "hot" and "neutral" lines in a circuit creates an electric field that can be measured, whose phase can be extracted, and whose magnitude can be estimated (after a calibration procedure). Earlier systems required costly postinstallation calibration, but we wondered just how important the calibration step—primarily required to scale the voltage magnitude—actually was.

We monitored voltage for over a month and found that it stayed within a small band. Moreover, the voltage signal, unlike the current signal, is quite sinusoidal, which means that it can be synthesized with higher fidelity. The most significant contribution to error in the power estimation was due to the phase offset between voltage and current. If this phase offset could be estimated accurately, it would be unnecessary to sample and scale the voltage signal. Rather, we could just synthesize a phase-aligned sinusoid and rely on linearly scaling the resulting power values if the voltage, monitored elsewhere, changed from the nominal voltage (which happens infrequently).

To test this idea and address several other drawbacks in Gemini, we designed Triumvi, a new circuit-level

power meter (see Figure 6). Triumvi improves on the Gemini design in several ways. First, it includes an integrated voltage sense channel, whereas Gemini relies on an external source for voltage parameters. Second, it multiplexes a single current transformer for both energy harvesting and current measurement, whereas Gemini requires two separate current transformers. Third, it stores measurements locally using FRAM, whereas Gemini transmits its measurements immediately. Finally, Triumvi encrypts its data transmissions with AES-128, whereas Gemini transmits the readings in the clear.

The result of this study is that in a form factor slightly larger than the split-core current transformers typically used to just measure current, Triumvi harvests enough energy to power itself, monitor current and voltage, calculate power, encrypt data, store data, and wirelessly transmit the results. Our prototype can sustain a sample rate of nearly 1 Hz when the load draws at least 400 W. Triumvi exhibits an average accuracy of 5.16 percent over a load power draw range of 150 to 600 W. Moreover, Triumvi supports rapid installation, requiring just 30 seconds to instrument a circuit and stream readings, which enables fast and inexpensive energy audits.

Plug-load metering. Miscellaneous electrical loads (MELs or plug loads) represent the fastest growing segment of electrical loads in homes and offices.[11] Unfortunately, we have limited visibility into the nature and extent of these loads. Monitoring plug loads is also useful for many things beyond characterizing loads—home energy audits, verifying energy star ratings in the wild, and detecting malware-infested medical devices are just a few other applications. Although it is possible to build Monjolo electricity meters in plug-load meter form—indeed, we have built dozens and deployed them in labs and homes—many applications are constrained by aesthetic

Figure 7. PowerCube, a cubic-inch plug-through power meter. Although this design achieved our volume target, it was difficult to assemble due to the use of six interlocking circuit boards that formed a cube.

and cost concerns that limit the viability of that approach to research settings. The two major aesthetic issues are size and usability. Plug-load meters, such as Kill-a-Watt and Watts up?, are too large for pervasive deployment and have too limited a user interface—an LCD screen or network data delivery—to be usable in home and office settings. So, we began to explore the scaling limits of plug-load energy meters to see how small we could make them.

Examining a variety of meter designs revealed that two main factors contributed to a meter's size. First, a roughly cubic inch volume is needed for a receptacle with which a plug load's plug could mate. Second, power supply capacitors account for a volume that is roughly proportional to a meter's power draw. This gave us a concrete miniaturization goal—a cubic inch volume—that we could target. With some engineering effort, we were able to squeeze in all the key elements of a power meter—power supply, voltage acquisition, current acquisition, power calculation, and radio transmission—into a cubic-inch device, called PowerCube (see Figure 7). The receptacle and capacitors dominated the internal volume, as expected. Although this design achieved our volume target, it was

difficult to assemble, so it went unused.

We had targeted a roughly cubic-inch volume for PowerCube based on the size of a receptacle. But what if a receptacle was not necessary? The existence of SafePlug tags—a plug-through PCB with a 1.0 inch × 0.4 inch footprint, to which an RFID chip is attached—made us wonder if a plug-through power meter was possible. There would be many challenges, for sure: making electrical contact with the plug prongs to obtain power, sensing voltage, and measuring current without intercepting the prongs. It would also require dramatically miniaturizing a mains-voltage AC-to-DC power supply and squeezing all the electronics for power metering and radio communications into an area smaller than a square inch.

However, it was possible, leading to PowerBlade,[12] the smallest, lowest cost, and lowest power AC plug-load meter that measures real, reactive and apparent power, and reports this data, along with cumulative energy consumption, over an industry-standard Bluetooth Low Energy radio (see Figure 8). Achieving the PowerBlade design point required us to revisit every aspect of conventional power meters. We needed

- a new method of acquiring voltage (spring-loaded, sideways-mounted prongs);
- a noninvasive, planar method of current measurement (measuring the voltage induced in a surface mount inductor);
- an efficient and accurate method of computing power from the voltage and current channels (implemented using a low-power microcontroller with FRAM to maintain cumulative energy across power cycles);
- a radio interface that leveraged nearby smartphones to display data and report it to the cloud (using EddyStone); and
- a traditional power supply reimagined with vastly lower current draw, allowing extreme miniaturization
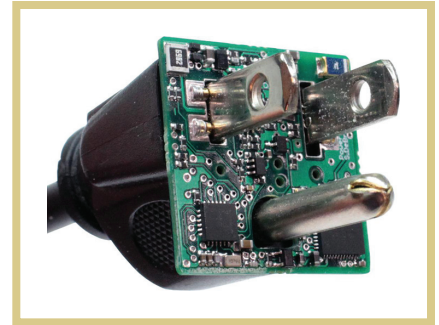
Figure 8. PowerBlade is essentially a two-dimensional and nearly invisible plug-through, plug-load power meter. It uses a microcontroller with nonvolatile ferro-electric RAM (FRAM) to maintain the cumulative energy total across power cycles. The measurements are reported over a Bluetooth Low Energy radio to a nearby gateway or smartphone for collection or processing.

but requiring operation reminiscent of energy harvesting.

PowerBlade occupies a 1.0 inch × 1.0 inch footprint, offers a 1/16″ profile, draws less than 180 mW itself, and offers 1.13 percent error on unity power factor loads in the 2 to 1,200 W range and a slightly worse error rate for non-linear and reactive loads. The system must duty cycle its radio because its miniature power supply cannot sustain continuous operation, but it does sample the voltage and current signals at 2.5 kHz. Because PowerBlade directly samples the AC voltage waveform, it can detect AC zero crossings and use these crossings as a synchronization signal to schedule communications—an area of future exploration. This new design point enables affordable large-scale studies of plug-load energy usage and is sleek enough for use by aesthetically-minded consumers. And, importantly, it is easier to manufacture than PowerCube. Variations on the theme include smart outlet covers that meter energy.[13]

Feel the Heat
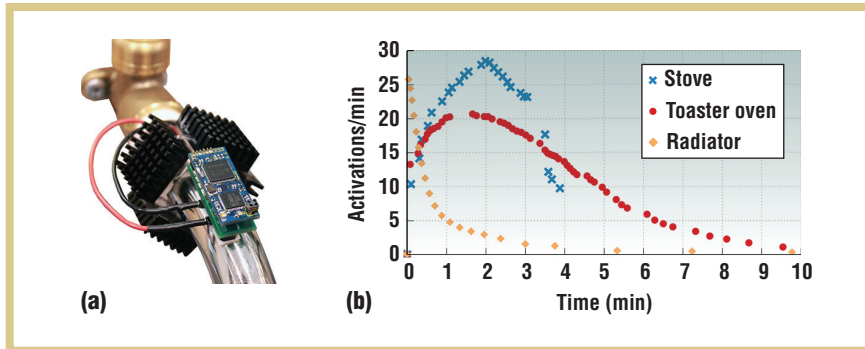Many appliances, including stoves, toasters, and radiators, emit heat in

Figure 9. A heat sensor based on the Monjolo approach. (a) A thermoelectric generator turns a temperature differential into current flow. The temperature difference between a hot surface and the surrounding cooler air can power a Monjolo sensor. (b) However, over time, as the air warms and heat sink saturates, the linear relationship between activation rate and temperature can be lost.
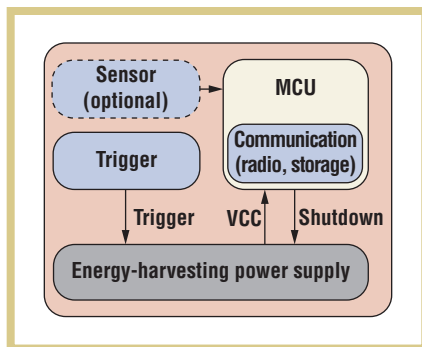

Figure 10. General sensor architecture. It contains four subsystems: energy harvesting power supply, trigger, sensor apparatus, and communications.

proportion to the electricity or gas they consume, and faucets and shower heads emit heat in proportion to the temperature and duration of their use. Could simple energy harvesting sensors that follow the Monjolo approach be used to monitor and infer the specifics of their operation? To find out, we designed a harvester for a thermoelectric generator and attached the sensor to various heat-emitting loads around a house (see Figure 9).[14] Our findings were illustrative.

Unlike harvesters that target light, electricity, or magnetism and respond quickly to a stimulus, harvesters that target temperature differentials respond more slowly. Heat sinks are often required for effective operation, but their thermal mass can be both a bless-

ing and a curse. A large heat sink does not saturate quickly, preserving the crucial temperature differential needed for thermoelectric generation, but it drives up system volume and surface area, and decreases responsiveness. A small heat sink is of course more responsive, but it can quickly saturate, reducing the magnitude of the temperature differential available to generate power. In addition to these challenges, the environment can also become saturated. For example, a hot shower elevates both the shower nozzle temperature and the ambient air temperature, reducing the power output.

Fundamentally, thermal inertia and equilibrium make thermoelectric generators less effective at adhering to the Monjolo approach during both transitional and steady-state operation. So do they have any value? It turns out that they do—as binary activity sensors. Small sensors, perhaps in the form of peel-and-stick tags, could be affixed to appliances and faucets to signal usage. They could be used to estimate the rough duration of a shower, for example. Their data might not offer high temporal fidelity, but such sensors could nonetheless give hints to disaggregation algorithms, helping deconstruct resource consumption in residential, commercial, or industrial settings.[15,16] They could also provide insights into machine malfunction, like

overheating. In such an application, a change in the distribution of activation intervals might signal when machinery is operating outside the norm.

Emerging Architecture

We have presented a wide array of energy harvesting sensors that extend the basic Monjolo design in various ways. All these sensors conform to a common architecture that has emerged through multiple generations of sensor development and deployment. The architecture is simple, but it has allowed us to build many of the sensors we have discussed in a modular fashion—innovating on only the unique aspects of the design space for each new system.

Figure 10 shows the architecture shared by our energy harvesting sensors. It contains four subsystems: energy harvesting power supply, trigger, sensor apparatus, and communications.[17] Collectively, this simple architecture captures the internal organization of the great majority of sensors discussed.

Energy Harvesting Power Supply

Each sensor accrues energy at runtime with a suitable energy harvesting frontend. Power supplies must expose a trigger, latch, and shutdown mechanism. Typically, energy harvesting power supplies supply power immediately after a voltage threshold is reached. For some applications, this might be useful, but other applications might only want to consume the limited energy reserves after a period of time has elapsed or an event has occurred.

To support this, the power supply must be able to store energy without activating the remainder of the sensor until a trigger is asserted. Once asserted, the power supply latches and keeps the power rail activated until energy is exhausted or the device asserts the shutdown signal to disconnect power. The power supply should also be capable of disabling this feature and supplying the power rail immediately after energy is available. In addition, power supplies can include provisions to increase the storage capacitor,

supply excess energy to a backup capacitor or battery, and dump excess charge to an auxiliary energy store or sink.

Trigger

The trigger is responsible for activating the computational, sensing, or communication resources on the device, depending on application needs. The trigger can fire as soon as sufficient energy is available or in response to an internal or external event, such as a real-time clock's periodic alarm or a random door opening. In this way, triggers can be opportunistic, periodic, or event-based.

Sensor

The energy harvester is the sensor for a purely Monjolo-style device. Alternatively, an on-board sensor can be used to monitor ambient conditions. The sensor's sample rate is constrained by the energy harvesting rate, and the range of usable sensors is governed by the energy storage capacity of the power supply. Low-power and low-energy sensors that can obtain a reading quickly are best suited for this architecture. If the sensor involves accessing the energy harvesting transducer, such as Triumvi, then the architecture's modularity could be compromised, and the sensor and power supply might need to be co-designed for the particular application.

Communications

Data communications could occur over space via wireless transmissions or over time by logging to local storage. The latter option is well suited to islanded or isolated operation, but it requires a low-energy, nonvolatile storage facility such as FRAM. Maintaining protocol sequence numbers across power cycles is another reason for having access to lightweight storage. Some network protocols will drop packets with duplicate sequence numbers, so it is important to give a unique number to each transmitted packet. Of course, this means that the sequence number must be inexpensively saved and restored across power cycle-separated activations.
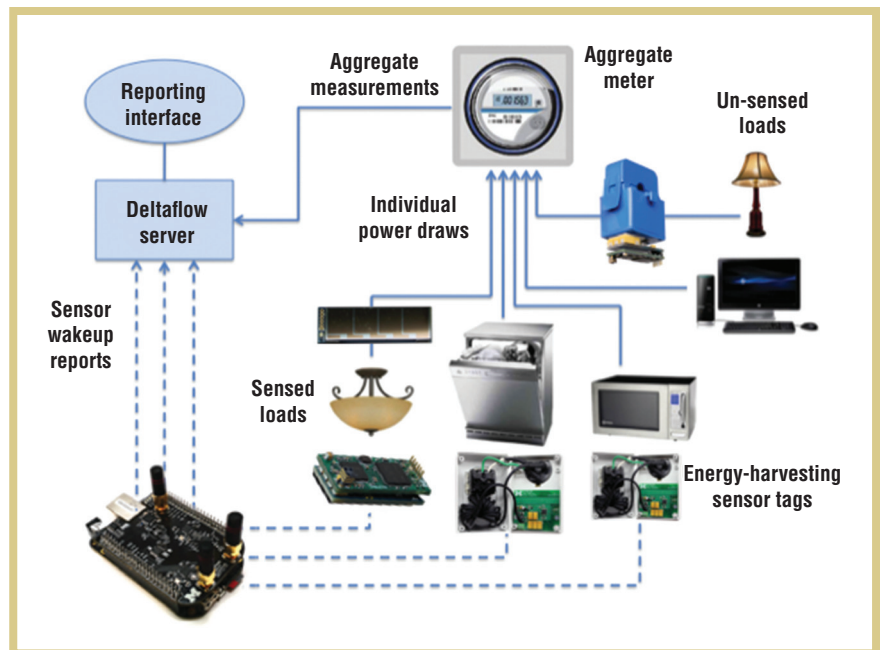

Figure 11. Submetering with Monjolo and Deltaflow. Although power flows from the meter to the loads, information about the power draw is aggregated at the meter (solid lines), while information about individual loads is encoded in the intermittent radio transmissions (dashed lines). These two data streams are combined to estimate the individual power draws.

From Sensors to Systems

So far, our focus has been on the sensors themselves, but for many of these sensors to be useful, they require assistance from nearby gateways. For example, Monjolo sensors without a real-time clock need the gateway to keep track of the interactivation intervals to estimate the activation rate. Or, the data from a network of Monjolo sensors might need to be processed to extract meaningful higher-level analytics. One example of such analytics is when various loads are instrumented in a home with Monjolo sensors, with the goal of submetering, as shown in Figure 11. We assume that each sensor will exhibit an activation rate that is correlated with the power draw of the load to which it is affixed. These sensors report their activations to the data-processing system, called Deltaflow, which can determine the actual power draw by incorporating ground-truth aggregate measurements such as those provided by a utility meter or Triumvi sensors.[18]

Algorithms map sensor activations to energy use by observing when the aggregate measurement and the sensor activation frequency change simultaneously. The algorithm iteratively partitions the history into discrete states that are used to construct and solve instances of a linear optimization problem. Solutions to the problem reveal the mapping from activation frequencies to individual load power draw. This systems approach to submetering results in installations that are easy to deploy and maintain, while contributing negligible additional load, enabling building owners and occupants to simply affix tags to energy consumers and automatically begin receiving real-time power-draw readings.

Ultimately, our goal is to replace the meso-scale Monjolo sensors with micro-scale, peel-and-stick sensors that incorporate the same functionality. While the current generation

Figure 12. A millimeter-scale "peel-and-stick" sensor tag. At this scale, the sensor could be integrated into laminated tags and easily, inexpensively, and invisibly affixed to pervasively distributed loads to realize perpetual sensing.

of Monjolo sensors are adequate, we envision a future generation of sensors that approach dimensions closer to "smart dust." Figure 12 shows an example of such a sensor, which integrates a solar cell, processor, radio, and battery, providing much of the Monjolo sensor functionality needed by Deltaflow to perform submetering.[19] This illustrates that the peel-and-stick sensor tags we envision will soon be viable, and at those scales, the sensor could be integrated into laminated tags and easily, inexpensively, and invisibly affixed to pervasively distributed loads to realize perpetual sensing. P

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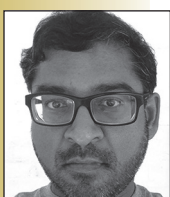
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