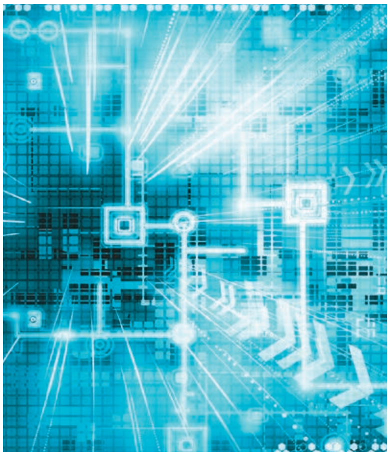

Batteries Not Included: Powering the Ubiquitous Computing Dream

Steve Hodges, *Microsoft Research Cambridge*

Mobile devices can never become truly ubiquitous without a suitably "invisible" power source.

Mark Weiser's vision of ubiquitous computing—a world where smart devices are all around us, woven invisibly into the fabric of everyday life—is slowly becoming a reality. Enabling factors include the increasing sophistication of ubiquitous computing hardware along with the growing complexity of the software running both on the devices and on the systems to which they're connected.

However, regardless of whether you consider invisible computing to be the realm of devices that truly can't be seen or if you include those in plain sight that people never look at, supplying power without encumbering the user is an ongoing challenge. This is especially true for wearable devices such as wireless headsets, smart watches, health monitors, and lifeloggers; peripherals like keyboards, mice, and remote controls; stand-alone devices including e-readers, digital cameras, and satellite navigation systems; and communication devices such as smartphones, cordless phones, and wireless webcams.

Fortunately, numerous established and emerging technologies could help in the quest to power the ubiquitous computing dream.

Many mobile devices exclusively rely on the rechargeable lithium-ion battery, and we've become so accustomed to charging our devices at night that it's part of our daily lives. As everyone knows, however, overlooking this simple but important ritual can cause significant inconvenience the following day. Some interesting areas of research aim to mitigate this inconvenience, primarily by providing methods for recharging Li-ion batteries more quickly and easily.

There's also a range of alternatives to rechargeable batteries, and with the growing diversity of ubiquitous computing applications, some of these approaches to battery-free operation might prove to be increasingly relevant in the coming years.

BATTERY TECHNOLOGIES

While watches, clocks, remote controls, and a few other devices typically use disposable batteries, rechargeable batteries are essential in today's mobile computing. And currently, about 70 percent of rechargeable batteries used in mobile devices are lithium-ion.

There are many factors to consider when comparing different rechargeable battery technologies, including lifetime, rate of discharge when not in use, safety, and cost. However, undoubtedly the most visible to the user is energy storage capacity per unit volume.

In this regard, battery technology greatly diverges from Moore's law: a mere 5 percent increase in capacity over a year is considered good. Exceptions tend only to occur when a new underlying chemistry is introduced—for example, since the transition from nickel to lithium around the turn of the century, battery energy density nearly doubled (P. Lee and D. Stewart, "Technology, Media & Telecommunications Predictions: 2011," white paper, Deloitte, 2011).

Researchers regularly demonstrate subtle changes in Li-ion battery chemistry that yield small capacity improvements, but these optimizations can take years to make it from the lab to the mass market due to stability, manufacturability, safety, and regulatory

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requirements, especially for larger-capacity batteries.

Thin-film “solid state” batteries are an interesting development that could underpin the next phase in rechargeables. With solid electrolytes, these batteries offer higher energy density than the established liquid and polymer electrolyte batteries and also have greater form-factor flexibility. If researchers can address certain issues such as affordability and temperature sensitivity, solid-state batteries with two to three times the capacity of today’s Li-ion cells could be commercially available by the end of this decade (http://green.autoblog.com/2011/10/07/solid-state-battery-updates).

Graphene-based batteries also promise higher energy densities if they can be manufactured at scale.

Another promising technology is the fuel cell, which is refilled with a chemical fuel such as hydrogen, natural gas, or methanol rather than recharged electrically. Practical concerns have likewise limited the commercial adoption of fuel cells for small portable devices to date, but if these can be overcome there will be a step-change in battery capacity.

MORE CONVENIENT RECHARGING

No matter how much capacity a battery has, at some point it will need to be recharged. Making this process less onerous is an important ubiquitous computing enabler.

One approach is to accelerate the recharging process. Unfortunately, there are fundamental limits on the rate for transforming electrical energy back into chemical energy within the cell. Exceeding these limits typically starts to shorten the battery’s lifetime, degrading its capacity and potentially compromising safety. However, ongoing research into graphene-based chemistries could ultimately provide a route to shorter recharge times (http://energy.gov/americas-next-top-energy-innovator/vorbeck-materials-corp).

Super- or ultracapacitors are a promising alternative to rechargeable batteries. They can be used to power an electronic device and subsequently be recharged. However, unlike typical batteries, they can receive and deliver energy very quickly. This supports charging a mobile device just before use and then easily “topping off” the charge subsequently if necessary.

Figure 1. The Genius DX-ECO wireless mouse uses a supercapitor instead of batteries, enabling ultrafast recharging.

Supercapacitors have been in development for more than 50 years, but recent advances, partly driven by the electric vehicle industry, have pushed energy density up to new levels. Although still an order of magnitude lower than that of regular batteries, the convenience of very fast recharging could outweigh this disadvantage for certain applications. Figure 1 shows an example of one such application, the battery-less, rechargeable DX-ECO wireless mouse by Genius (http://geniusnet.com).

In addition to reducing recharge times, another way to make recharging more convenient is to simplify the process of putting a device on charge. Innovations like magnets that automatically snap the charging cable into the correct socket can help with this.

ARE TWO BATTERIES BETTER THAN ONE?

An alternative to ultrafast recharging is to physically swap an exhausted battery for a fully charged one. Many users already routinely do this, especially for devices like laptop computers and digital cameras. Swapping batteries, however, is cumbersome, especially if you’re in the middle of carrying out a task. And if you have multiple devices with different types of batteries, there’s the added burden of carrying numerous replacements when you’re on the go. In addition, the recent trend toward highly integrated and nonremovable batteries means replacing batteries is no longer an option in some cases.

To address this problem, companies such as Energizer (http://energizerpowerpacks.com) and Revolve (http://revolveusa.com) have developed portable external batteries that can be used to recharge mobile devices on the fly. Figure 2 shows the Energizer XP18000, which features an 18,000-mAh battery and multiple outputs capable of charging a range of devices such as smartphones, laptops, and cameras.

BATTERY-FREE OPERATION

Perhaps the ideal solution for powering mobile devices is energy harvesting, which enables battery-free operation. Previous research investigated the feasibility of harvesting energy from numerous sources including vibration, solar cells, and Peltier junctions (J.A. Paradiso and T. Starner, “Energy Scavenging for Mobile and Wireless

Figure 2. The Energizer XP18000 is a portable external battery than can be used to recharge multiple mobile devices anytime, anywhere.

Figure 3. The Peppermill is a general-purpose wireless input device that derives both power and control information from manual rotary input.

Electronics," *IEEE Pervasive Computing*, Jan. 2005, pp. 18-27). Of course, each of these examples requires the relevant form of energy to be available in the environment—physical movement, infrared radiation, and temperature differentials, respectively.

In devices such as wireless sensors that monitor industrial machinery, energy harvested from vibrations or thermal differentials can be reliable enough to provide power continuously. When the power source is intermittent, however, a temporary energy storage device such as a battery or capacitor is necessary.

Some devices can harvest energy directly from the user rather than the environment. Familiar examples include wind-up radios and flashlights, but more interesting is a range of emerging devices that harvest power as the user operates them. For example, EnOcean makes wireless light switches that harvest energy from linear motion (www.enocean.com/en/motion-energy-harvesting). Figure 3 shows the Peppermill, a general-purpose wireless input device that derives both power and control information from manual rotary input (N. Villar and S. Hodges, "The Peppermill: A Human-Powered User Interface Device," *Proc. 4th Int'l Conf. Tangible, Embedded, and Embodied Interaction* [TEI 10], ACM, 2010, pp. 29-32).

SUPPLYING POWER WITHOUT CABLES

A variant of energy harvesting involves injecting energy into the environment with the explicit aim of providing power to one or more remote devices. Inductive charging is gaining popularity due to improvements in power transfer rates coupled with recent standardization across the industry that allows interoperation of chargers and devices from different manufacturers.

The range of inductive power transfer is inherently limited due to the dramatic fall-off of magnetic field strength with distance. However, it's possible to leverage an electromagnetic field's self-propagating nature to provide power much farther away. An early widespread application of this technology was the crystal radio. Based on a single semiconductor junction, this device harvested power from the electromagnetic radiation that also carried an audio broadcast.

Crystal radios aren't in common use today, but radio-frequency identification relies on a similar approach. An RFID reader can be coupled to an antenna that emanates energy into the local environment for any nearby RFID tags to harvest. Once powered, the RFID chip can use load modulation or backscatter to send information back to the reader.

Researchers at Intel Labs and the University of Washington extended the RFID concept to create a general-purpose wireless identification and sensing platform (WISP), which is powered from and communicates with a nearby radio transmitter (A. Sample and J.R. Smith, "Experimental Results with Two Wireless Power Transfer Systems," *Proc. IEEE Radio and Wireless Symp.* [RWS 09], IEEE, 2009, pp. 16-18).

This work is now being extended to increase the range and amount of power that can be delivered wirelessly with the ultimate aim of providing wireless power to mobile devices in indoor environments (A.P. Sample, D.A. Meyer, and J.R. Smith, "Analysis, Experimental

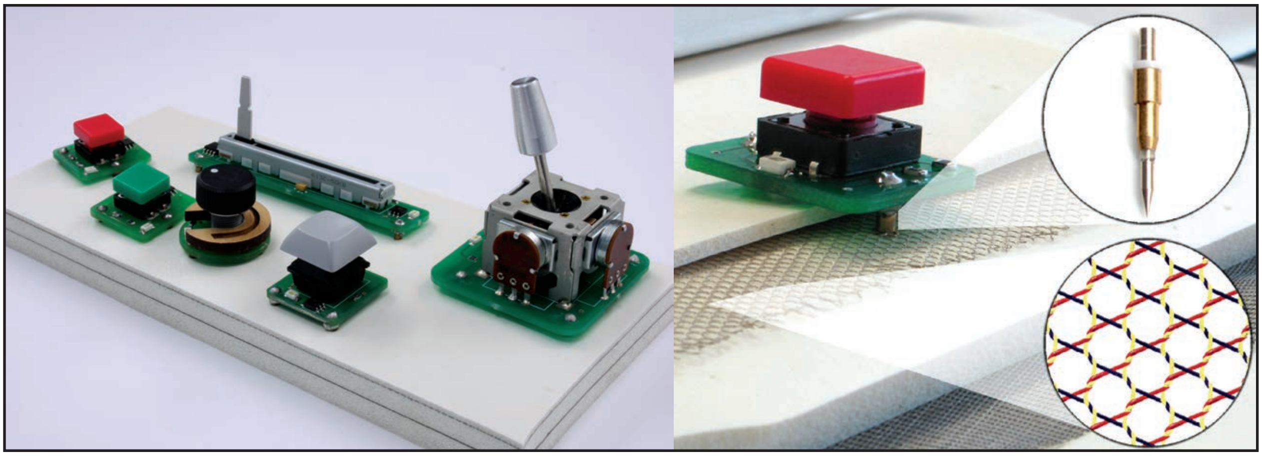

Figure 4. The VoodooIO project investigated small, battery-less electronic input controls and display elements with one or more physical pins protruding from them. These pins connected electrically with conductive mesh layers in the substrate when inserted, thereby supplying power and data. (Photo courtesy of Nicolas Villar.)

Results, and Range Adaptation of Magnetically Coupled Resonators for Wireless Power Transfer," *IEEE Trans. Industrial Electronics*, vol. 58, no. 2, 2011, pp. 544-554).

The VoodooIO project took a different approach to powering a collection of devices embedded in the environment without running wires to each one (N. Villar and H. Gellersen, "A Malleable Control Structure for Softwired User Interfaces," *Proc. 1st Int'l Conf. Tangible and Embedded Interaction* [TEI 07], ACM, 2007, pp. 49-56). As Figure 4 shows, small, battery-less electronic display elements and input controls like push-button switches had one or more physical pins protruding from them. These pins connected electrically with conductive mesh layers in a substrate when inserted, thereby supplying power and data.

In a similar vein, the Networked Surfaces project augmented physical surfaces such as desks with networking capability and power sources (J. Scott et al., "Networked Surfaces: A New Concept in Mobile Networking," *Mobile Networks and Applications*, vol. 7, no. 5, 2002, pp. 353-364). As Figure 5 shows, researchers outfitted mobile devices such as laptops, PDAs, and digital cameras with special hardware that made direct electrical contact with conductors on the surface.

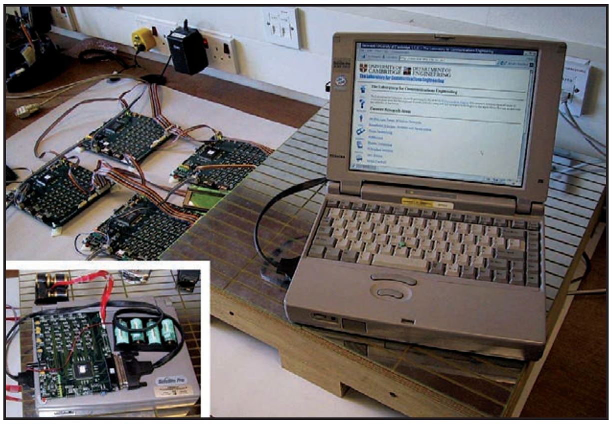

Figure 5. In the Networked Surfaces project, researchers outfitted mobile devices such as laptops, PDAs, and digital cameras with special hardware that made direct electrical contact with conductors on a physical surface such as a desk. (Photo courtesy of James Scott.)

As we strive to realize the ubiquitous computing vision, where mobile devices all around us work continuously and autonomously on our behalf, it's easy to overlook the very practical issue of power. But mobile devices can never become truly ubiquitous without a suitably "invisible" power source.

Batteries will continue to improve, albeit largely incrementally. But other technologies could reduce the inconvenience associated with batteries, in some cases completely eliminating the need for them. Given the diverse requirements of ubiquitous computing applications, these technologies will increasingly complement the currently pervasive Li-ion battery. ■

Steve Hodges *leads the Sensors and Devices research group at Microsoft Research Cambridge, UK. He is also a visiting professor at the School of Computing Science, Newcastle University, UK. Contact him at steve.hodges@microsoft.com.*

Editor: Albrecht Schmidt, University of Stuttgart, Germany; albrecht@computer.org