Green at the Micro-Scale: Powering Pervasive Computing Systems Through Environmental Energy Harvesting

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Mark Weiser's vision for pervasive computing, eloquently described in his landmark 1991 paper, was one where humans would be surrounded by thousands of pervasive computing devices that silently weave information technology into the very fabric of our lives. One of the biggest show-stoppers to realizing this vision is the problem of powering these thousands of pervasive computing devices. Most of today's pervasive computers are battery powered. Despite the extreme constraints on size (and hence battery capacity), next-generation pervasive computing systems will be required to operate for several months to years without the need for battery replacement, because frequent battery replacement for thousands of devices is not only infeasible, but also completely contradicts Mark Weiser's vision of pervasive computing as a technology that does not constantly require human intervention. Given that battery technology is projected to improve at a very slow rate, going forward, the battery-powered nature of these systems will pose a significant challenge.

This white paper makes the case that the only feasible option to conveniently power next-generation pervasive systems is to scavenge energy from ambient sources (e.g., solar radiation, thermal gradients, radio frequency transmissions, vibrations). Carefully designing pervasive computing systems to operate off scavenged energy has the potential to result in perpetual (also referred to as net-zero energy, self-sustained, or energy-neutral) system operation. In addition to greatly decreasing the maintenance cost and inconvenience associated with frequent battery replacement, this also has significant environmental implications. For example, the Environment Protection Agency reports that every year, more than 3 billion batteries are discarded in the USA and that placed end to end, discarded AA batteries would circle the earth six times. Dry cell batteries are also responsible for about 88 percent of the total mercury and 50 percent of the total cadmium deposited into US solid waste landfills. This represents a potential long-term threat to groundwater and drinking water supplies. The use of energy harvesting to power pervasive computing systems greatly decreases (and in some cases, completely eliminates) the dependence on batteries and directly helps mitigate their harmful environmental impact.

While the notion of energy harvesting has been extensively explored in the context of large systems such as solar farms, windmills, and hydro-generators, *micro-scale energy harvesting*, as a systematic discipline, remains largely unexplored. Realizing efficient micro-scale energy harvesting systems is challenging due to several factors. First, the form-factor constraint in these systems mandates the use of highly miniaturized energy transducers (at most a few cm^2 or cm^3). As a result, the output voltage of the transducer is very low, often far less than 1V. For example, miniature photovoltaic cells and thermo-electric generators produce voltages in the range of 0.2-0.6V. Extracting energy from such ultra-low voltage sources is a non-trivial task. Second, the maximum power output of these micro-scale transducers is also extremely small, often only a few mW. Therefore, the energy harvesting subsystem should be carefully designed to extract as much power as possible from the transducer and provide it to the pervasive computing system with minimal loss. This is particularly difficult to do because energy transducers, e.g., solar cells, and energy storage elements, e.g., batteries, exhibit different electrical characteristics, which must be matched to each other to maximize harvesting efficiency. Third, because environmental energy supply is highly time varying in nature (e.g., changing light intensity significantly impacts the output power from solar cells), the ability of the pervasive computing system to modulate its power consumption through the use of harvesting-aware power management techniques plays a crucial role. Finally, battery non-idealities, such as self-discharge and round-trip efficiency, also directly affect energy usage and storage decisions.

We strongly believe that overcoming the challenges described above requires a concerted research effort involving all layers of the design hierarchy, ranging from devices, circuits, and architectures to power management algorithms and design exploration frameworks. In particular, we believe that the analysis, design, and management of environmentally powered micro-scale systems will involve the following key research aspects or thrusts:

Efficient power extraction: The first key research direction involves the design of new techniques for efficient power extraction from micro-scale energy transducers. For example, developing new architectures for ultra-low voltage power converters and maximum power point tracking schemes (think of maximum power point tracking as a form of impedance matching to maximize power transfer) that are suited to the electrical characteristics exhibited by energy transducers.

Efficient energy storage: The second key research thrust addresses efficient storage of the harvested power. For example, exploring new energy storage architectures that synergistically combine heterogeneous energy storage elements (e.g., thin film batteries and ultra-capacitors) to minimize losses during energy storage.

Efficient energy consumption: This research direction involves the exploration of new *harvesting-aware* power management techniques . The key challenge is to account for the spatial and temporal variations in energy availability and modulate system performance/power consumption accordingly, with the goal of self-sustained operation.

Enabling systematic design space exploration: This research thrust involves the creation of design methodologies and tools that enable systematic design space exploration of micro-scale energy harvesting systems. This thrust is essential to transforming the study of micro-scale energy harvesting systems from an art that relies on designer intuition into a systematic science. The first step in doing this is to develop simulation models of various system components (e.g., various energy transducers, power converters). These models can then be used to create simulation tools that allow designers to quickly evaluate the impact of various design choices and parameters while architecting micro-scale energy harvesting systems. These design tools can also be used to analyze the requirements for a micro-scale energy harvesting system to be self-sustaining (e.g., verifying whether the system is harvesting enough energy for it to never run out of power).

We are confident that significant advances in the research directions described above will allow us to fully realize the potential of micro-scale energy harvesting and greatly reduce (possibly, even eliminate) the need for battery replacement in next-generation pervasive computing systems, removing one of the biggest showstoppers to their large-scale adoption. Successful completion of the proposed research vision will also achieve significant environmental impact by greatly reducing the large number of batteries that are discarded every year.

Participant Background: Vijay Raghunathan has published extensively on the topic of environmental energy harvesting systems and low power embedded system design. He has presented full-day tutorials, embedded tutorials, invited talks in academia and industry, and has organized special sessions at leading ACM/IEEE conferences on the topic of micro-scale energy harvesting. He led the design of the HELIOMOTE, one of the first energy harvesting wireless sensor nodes. The HELIOMOTE design has been commercialized and used in several environmentally-powered wireless sensor network deployments. The HELIOMOTE design was also awarded the design contest award at the ACM/IEEE International Symposium on Low Power Electronics and Design in 2005.