Prototyping Energy Harvesting Active Networked Tags (EnHANTs) with MICA2 Motes

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***Abstract*—With the convergence of ultra-low-power communications and energy-harvesting technologies, networking self-sustainable ubiquitous devices is becoming feasible. Hence, we have been recently developing new devices, referred to as Energy Harvesting Active Networked Tags (EnHANTs). These small, flexible, and energetically self-reliant tags can be seen as a new class of devices in the domain between RFIDs and sensor networks. EnHANTs are made possible by advances in ultra-low-power ultra-wideband (UWB) communications and in organic semiconductor-based energy harvesting materials. They will enable novel tracking applications, such as continuous monitoring of objects and locating misplaced items. In this demo, we present phase I EnHANT prototypes. These prototypes are much larger than the envisioned EnHANTs and do not include custom-made UWB and organic electronic components. Yet, they serve as platforms for preliminary experiments and allow demonstrating *energy harvesting-adaptive* EnHANT communications. Each prototype is based on a MICA2 mote and includes a custom-designed sensor board with a light sensor and a solar cell, which are used to determine the light energy received from the environment. We have also designed a monitoring system which is used in the demo to show how the EnHANT prototypes adjust their communications patterns based on their energy harvesting parameters.**

***Index Terms*—Energy harvesting, energy scavenging, energy adaptive networking, ultra-low-power communications, active tags, solar energy, indoor light.**

I. Introduction

Energy Harvesting Active Networked Tags (EnHANTs) belong to the domain between RFIDs and sensor networks [12]. Small, flexible, and energetically self-reliant, EnHANTs will be attached to objects that are traditionally not networked, such as books, furniture, walls, doors, toys, keys, produce, and clothing. In their capacity as *active tags*, EnHANTs will enable ubiquitous networking of commonplace objects, and thus will provide the infrastructure for novel tracking applications, such as locating misplaced items, continuous monitoring of objects, and determining locations of disaster survivors. Recent advances in ultra-low-power circuit design, ultra-wideband (UWB) wireless communications [10], and organic energy harvesting techniques will enable the realization of EnHANTs in the near future. Additional information about the EnHANTs project is available at [2].

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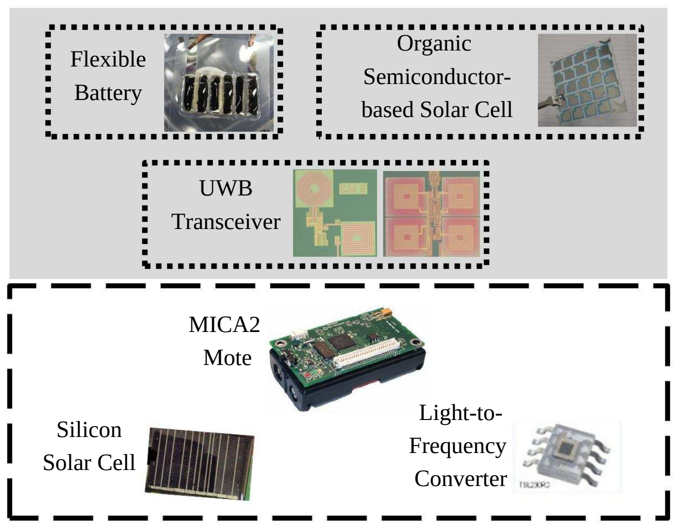


Fig. 1. The components of the envisioned EnHANT phase II prototype (top, shaded) and the components of the phase I prototype (bottom).

In this demo, we present phase I EnHANT prototypes that are based on commercial-off-the-shelf (COTS) hardware. The hardware components of the EnHANT prototypes we present in this demo are shown schematically in Fig. 1 (bottom), and a sample prototype in shown in Fig. 2. The long-term objective is to create a small and flexible tag with the custom hardware integrated. Hence, phase II EnHANT prototypes will incorporate organic semiconductor-based solar cells, flexible batteries, and UWB transceivers, as shown schematically in Fig. 1 (top, shaded). These specialized hardware components are currently being developed (e.g., the solar cell and the battery we recently designed are shown in Fig. 3). The phase I prototypes we present in this demo serve as a platform for the integration of custom-designed hardware as well as for experiments with *energy harvesting-adaptive* EnHANT communications and networking.

One of the key enabling technologies for EnHANTs is energy harvesting, which allows perpetual operation of devices

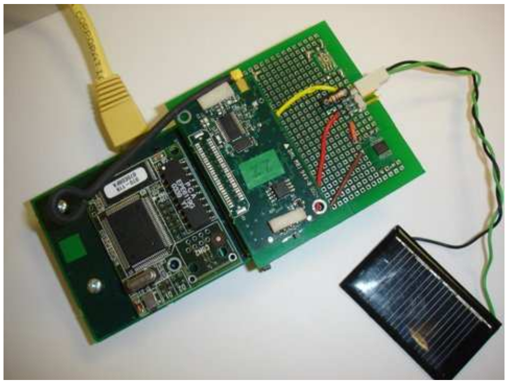
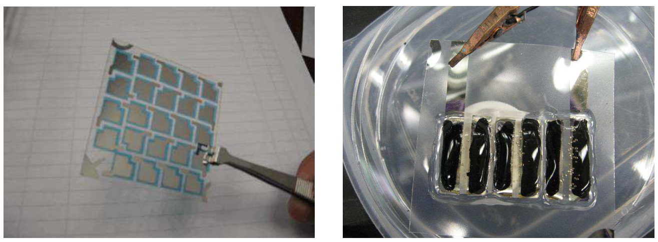


Fig. 2. The phase I EnHANT prototype attached to an MIB600 programming board.



(a) (b)

Fig. 3. (a) An organic semiconductor-based small-molecule solar cell [13] and (b) a thin-film flexible printable battery, both developed in the Columbia Laboratory for Unconventional Electronics.

and has recently attracted attention from industry [3], [4], [9] and academia [11], [14]–[20]. In traditional battery-based communications, the devices minimize energy spending to extend network lifetime. With energy harvesting, rather than minimizing energy consumption, the devices optimize the energy spending according to environmental conditions. The adjustments of energy spending in energy-harvesting systems can be done, for example, by varying the devices' duty cycles [15], [19], activation patterns [16], or data collection rates [11], [17]. Current sensor networking research on radiant energy harvesting mostly focuses on outdoor Solar energy. Since we expect many EnHANT applications to function indoors, the EnHANT research focuses on harvesting *indoor light energy*. In this demo, we show how the EnHANT prototypes adapt their communication patterns to the energy they can harvest from the environment. A particular challenge in energy harvesting-adaptive communications of ultra-low-power devices is the tight dependency between energy spending rates of the communicating devices [12]. We demonstrate EnHANT prototypes exchanging information about their energy states, and making *joint decisions* on their communication patterns based on the exchanged energy parameters.

II. System Description

In this demo we present phase I EnHANT prototypes that are based on commercial-off-the-shelf (COTS) components. The current prototypes are implemented using MICA2 (MPR400) motes [1] and custom-designed sensor boards. A

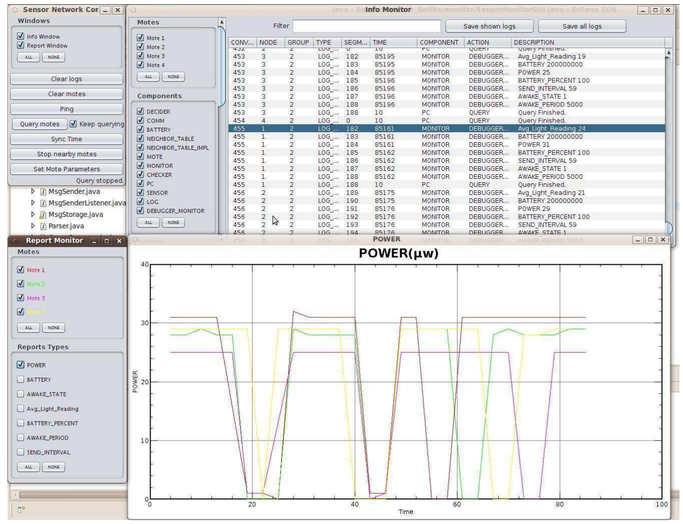


Fig. 4. Sample screenshot of the monitoring system user interface.

phase I EnHANT prototype is shown (placed on an MIB600 programming board [6]) in Fig. 2. It includes a solar cell and a TAOS TSL230rd light-to-frequency converter [8]. A light-to-frequency converter allows the prototypes to obtain accurate measurements of the environmental energy present, while the solar cells demonstrate how much of the available energy a particular harvesting technology collects. The accuracy of the energy measurements of the light-to-frequency converters has been verified using a Newport 818-UV photodetector [7] traceable to the National Institute of Standards and Technology (NIST).

The custom-designed sensor boards include a resistor and a MAX5455 digital potentiometer [5]. The board design allows to use a fixed resistor or the potentiometer to load the solar cell. In some experiments, we use the digitally controllable potentiometer to find the optimal cell loading for maximum power as illuminance changes. The voltage across the load resistor can be determined by the microcontroller's A/D converter and the actually harvested power can be determined.

At this stage, the phase I EnHANT prototypes are communicating with each other wirelessly using MICA2 transceivers. The phase I prototypes do not include a rechargeable battery, and therefore the EnHANT battery state is emulated using a *virtual rechargeable battery* software module, where the virtual battery level changes in response to a node spending energy on communications, or obtaining energy from the environment. The nodes exchange their identifiers and their energy harvesting-related parameters (i.e., virtual battery levels and power generated by the solar cells), and determine the communication rates in accordance to their energy states.

To easily configure the prototypes' parameters and to track their behavior, we have designed and developed a custom monitoring and control system with a Java-based graphical user interface. This monitoring system includes a set of 'live' graphs that are used to demonstrate the changes in

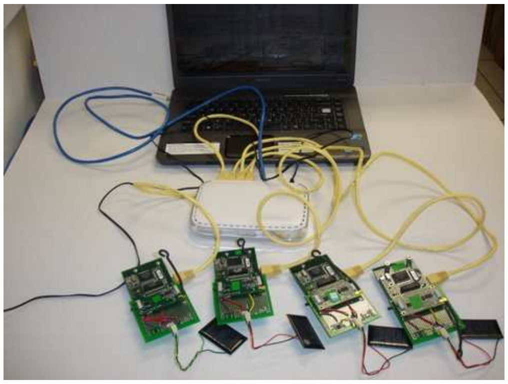


Fig. 5. Four phase I EnHANT prototypes placed on programming boards connected through an Ethernet switch to a computer running the graphical monitoring system.

nodes' communication parameters and energy states. A sample screenshot of the graphical user interface is shown in Fig. 4, where a graph depicting how the changes in environmental light conditions affect the power generated by solar cells of four different prototypes is shown. The monitoring system can access individual nodes via a wireless base station, or it can be used to track the parameters of the nodes that are placed on programming boards. With standard sensor boards, radiant energy-related hardware components cannot be used when a mote is placed on a programming board. The custom sensor boards we have designed allow using a solar cell and a light-to-frequency converter with the prototypes in this configuration. Since the changes in the parameters of prototypes placed on programming boards can be displayed in the graphical user interface with a very short delay, this setup allows for an interactive demonstration of energy harvesting-adaptive EnHANT communications.

III. Demonstration

In this interactive demo we show several phase I EnHANT prototypes communicating with each other. The prototypes determine how much power their solar cells are generating. Based on that, they determine their communication parameters. In order for the demo participants to be able to quickly observe the changes in communication parameters, the nodes are placed on MIB600 programming boards that are connected via an Ethernet switch to a computer running the monitoring system. The demo setup is show in Fig. 5.

Demo participants can change the environmental energy the devices receive by reducing or increasing the amount of light shining on the solar cells. The online monitoring system displays a set of graphs that represent the states of various prototype parameters, such as their communication rates. When changing the radiant energy levels, demo participants can observe how the changes in the environmental energy availability change the power generated by prototype's solar cell, and influence the prototype communication patterns. Demo participants can also observe how the changes in the energy available to a node influence the communication patterns of the other nodes communicating with it.

IV. Acknowledgments

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