Energy Monitoring in Smart Buildings Using Wireless Sensor Networks

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***Abstract*—In this work, we present the implementation and deployment of a wireless sensor network for the monitoring of electric energy uses in smart buildings. This wireless sensor network is based on our newly-developed *Granular Radio EnErgy-sensing Node* (GREEN), which consists of a micro-controller, a radio, a battery and a giant magnetoresistive (GMR) magnetic field sensor. The GREEN node can be easily attached to a current-carrying conductor for proximity-based electric current measurement. The intent of this article is to fully disclose the information regarding the design, fabrication and implementation of this GREEN-based wireless sensor network used as an electric energy monitoring system. It should be noted that the wireless sensing platform is not limited to energy monitoring, but can also be well adopted in other applications and deployment settings.**

Keywords–Smart Building, Wireless Sensor Networks, Energy Sensing

I. Introduction

Energy efficiency in smart buildings relies on a reduction in overall usage and also Demand Response (DR) to offset non-essential peak energy usage. These economic goals then depend on information about the energy usage of individual appliances. Retrofitting existing systems for commercial buildings and households requires that voltage and current sensing devices be as non-intrusive as possible for ease of integration and ease of deployment. Presently, buildings are retrofitted by installing clamp-on submeters into circuit breaker panels to monitor the electricity usage in each individual circuit. However, the installation of such systems is very expensive as it requires the use of certified electricians and a scheduled shutdown of electrical services. In our previous work [1], [2], we proposed a stick-on submetering system that allows the electric currents going through the circuit breakers to be measured from multipoint magnetic field measurements on the surface of breaker panels (also see in Fig. 1). Since the sensors can be easily attached on the surface of panels, the installation cost of this system is one-tenth the cost of any clamp-on meters. There are many commercially available wireless platforms [3], [4], [5], [6], [7] that can be used to establish a wireless sensor network for transmission of data collected from the circuit breaker stick-on sensors. However, as the available space on the circuit breaker panels is often limited, the footprint of the entire wireless sensor node is desired to be as small as possible and none of the commercial platforms has so far met this requirement. Therefore, a compact wireless sensor node, called "The Granular Radio EnErgy-sensing Node (GREEN)" was designed and fabricated. With a footprint of only $1cm^2$, it allows for easy installation and more accurate placement, which in turn allows for increased granularity of measurements of the electric currents [8]. This paper presents complete information on the operation and programming of the nodes. It can be seen that they can be used widely in smart building applications and many other "smart environments". The remainder of the paper is structured as follows, Sec. II presents the specific wireless technology that we've developed for the smart buildings. In Sec. III, we describe the wireless sensor networks and the lightweight mesh networking. In Sec. IV, we show an example of the wireless monitoring and the stack of prototypes it employs to transmit the data. Lastly, in Sec. V, we summarize our findings and show directions of future work.

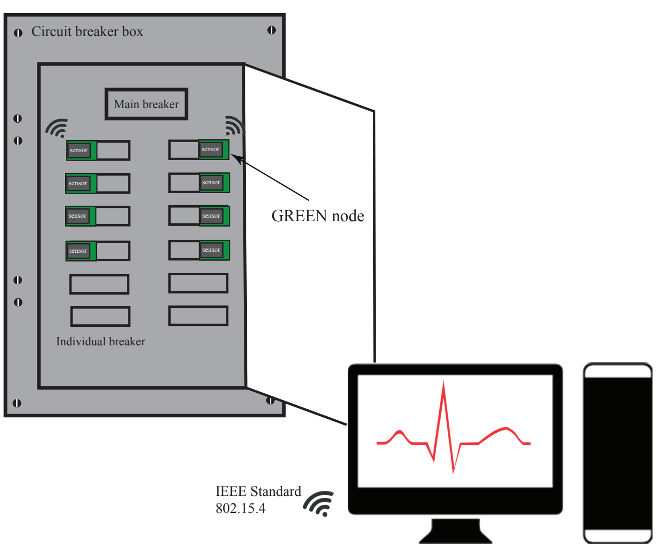

Figure 1: Schematic of a GREEN-based stick-on electricity monitoring systems for circuit breaker panels.

II. Specific Technology to Support Smart Buildings

Granular Radio EnErgy-sensing Node (GREEN, see Fig. 2) is a $0.56cm^3$ wireless stick-on node for non-intrusive energy monitoring applications [3]. Our target application is to wirelessly monitor the electricity usage from electrical circuit

 ISBN: 978-1-61208-363-6

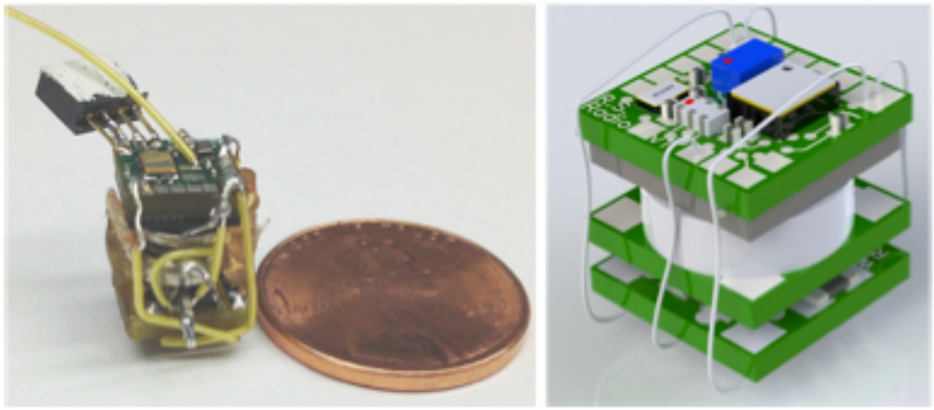

Figure 2: GREEN beside a 1-cent coin (left) and GREEN 3D model [8]

breaker panel, power cords of any device (lighting, appliances, electric vehicles, etc.), and critical loads on distribution and transmission cables. Shown in Fig. 3 are GREENs three

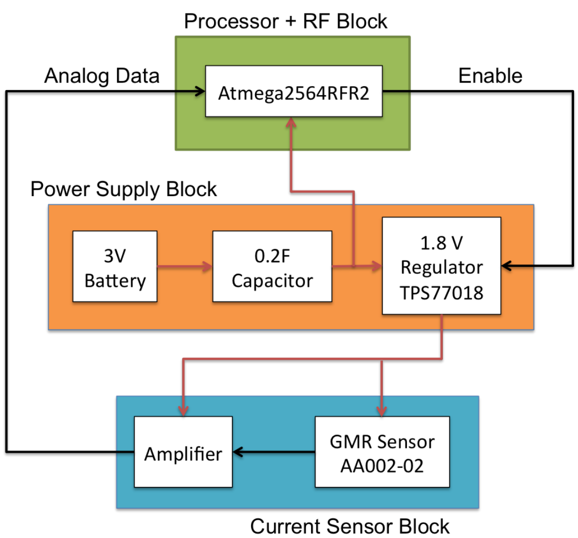

Figure 3: GREEN block diagram

main blocks along with the components that comprise each block. An analog AA002-02 GMR (Giant Magnetic Resonator) sensor from NVE Corporation is the main component of the Current Sensor block. This is interfaced to an Atmel Atmega2564RFR2 microcontroller with integrated Zigbee-compliant radio. The sizes of these two main component chips together with a $3V$ coin cell battery and a capacitor allowed the GREEN node to have a very small form factor, as shown in Fig. 4. Despite its size, the GREEN microcontroller/radio board (Fig. 4) managed to contain the common digital serial communications (I2C, SPI, USART) that are available in the Atmega2564RFR2 chip. One port is readily available for analog input, but the 4-pin programming port can also be configured for analog interfaces, if needed. All ports can also be used as basic digital input/output interfaces. This makes

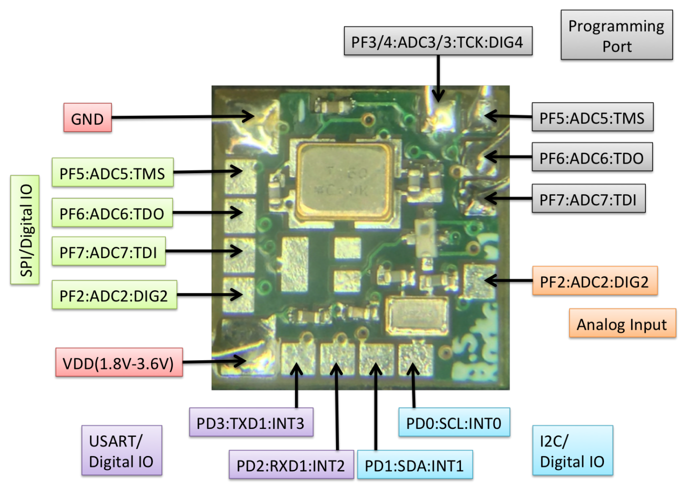

Figure 4: GREEN microcontroller/radio board pin layout

the microcontroller/radio board flexible to be interfaced with different types of sensors and configurable for other types of applications.

III. Wireless Sensor Networks (WSN) & Lightweight Mesh

Fig. 5 shows an example of the wireless sensor network (WSN) deployed in our work on smart buildings. In deploying a wireless sensor network using GREEN, we used the Lightweight Mesh (LWMesh) software stack [9], [10] provided by Atmel. BitClouds Zigbee Pro Stack [11] could also be used, but it requires some porting since the Atmega2564RFR2 is not readily supported. LWMesh software stack has provided programming templates in C for peer-to-peer and basic wireless sensor mesh networks. In this implementation, we used the wireless sensor network configuration. The provided projects are already arranged as project files for the Atmel Studio IDE. Although the templates are configured for Atmega256RFR2, the same can be used for Atmega2564RFR2 (used in GREEN) since they are both practically in the same family. To create a wireless sensor network using LWMesh, three types of nodes are created: non-routing nodes (end devices), routing nodes (routers) and coordinator. End devices can receive or transmit data when in range, but may not be available all the time (in sleep modes, limited power). Nodes with routing capabilities usually have continuous power and they relay the data coming from other router nodes or an end device to a coordinator. Coordinator/gateway nodes usually have continuous power and directly interface with a server machine (computer). The software stack can theoretically accommodate up to 65,535 nodes in one network. The address space is divided to non-routing and routing nodes. For routing nodes, 0x0001 to 0x7FFF addresses can be assigned, while 0x8000 to 0xFFFF are used for end devices. Address 0x0000 is used for the coordinator node. The current state of GREEN requires the use of Atmels JTAGICE 3 (or compatible programmer) to effectively program and configure the individual nodes. Future works would include the use of On-the-Air (OTA) programming for firmware update and easy online reconfiguration, when needed, especially if a very dense network is deployed. A native routing algorithm is already present in LWMesh. This made our work easier to test the capability of the GREENs in building a sensor network. Routing tables are automatically created and updated when data is being routed. The routes created by the algorithm may not be optimal.

IV. WSN Monitoring and Protocol

LightWeight Mesh follows the IEEE 802.15.4 standard frame format, but not the protocol stack itself. LightWeight Mesh cannot receive and process IEEE 802.15.4 command frames. Fig. 6 shows the general LightWeight mesh frame format used by each node.

For the current setup, the data received by the coordinator node is passed to the server (PC) via serial port. Fig. 7 shows the data format sent by the coordinator to the server. User programs able to access serial ports can now interpret this data. For the network topology visualization, we used the WSNMonitor software program from BitCloud. This monitoring software can show the real time topology formed network and the sensor readings received by each node. It can also show the RSSI and LQI for each link. Fig. 8 shows a sample screenshot of the WSNMonitor Software, depicting the nodes and links formed by the network.

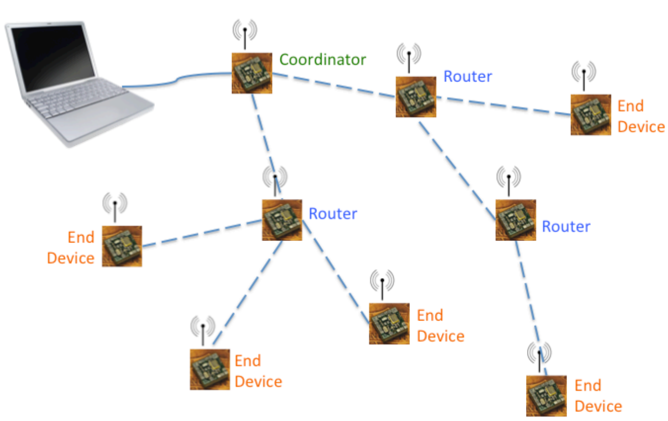

Figure 5: A sample wireless sensor network

16	8	16	16	16	8	8	16	16	4	4	0/16	Variable	0/32	16
Frame Control	Sequence number	PAN ID	Destination Address	Source Address	Frame Control	Sequence number	Source Address	Destination Address	Source Endpoint	Destination Endpoint	Multicast Header	Variable	MIC	CRC
MAC Header					Network Header							Payload	MIC	CRC

Figure 6: LightWeight mesh frame format

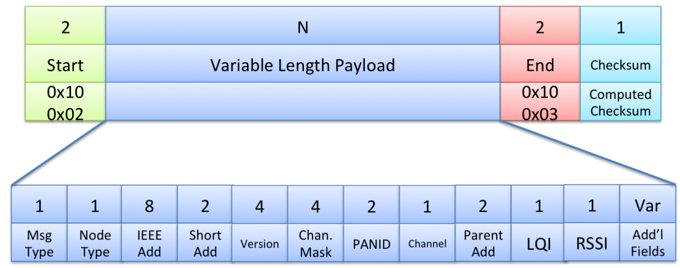

Figure 7: Data format

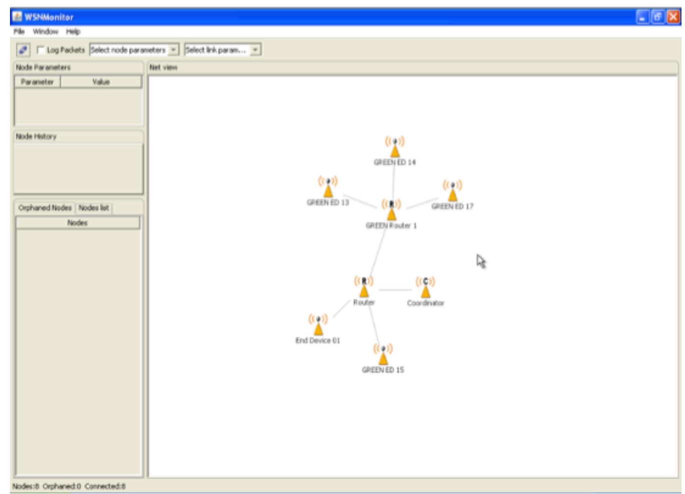

Figure 8: An example of the WSNMonitor Software

A logging program using Python to monitor the battery

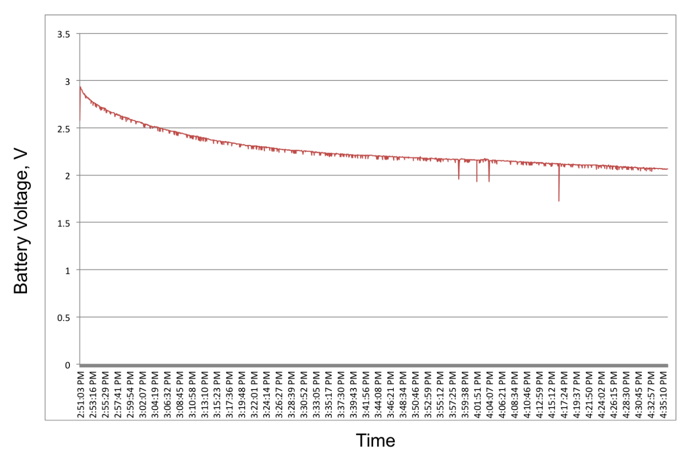

Figure 9: Battery discharge curve: a coin-cell battery is able to sustain the operation of the GREEN node continuously for about 1 hr and 45 mins.

voltage of end nodes was also created. Fig. 9 shows a sample battery voltage profile of an end node. The node is transmitting data every two seconds using the default format of the LightWeight mesh stack (approximately 10ms) and then goes to deep sleep mode. The node lasted for about 1 hour and 45 minutes in this example.

V. Conclusion and Future Work

The GREEN device is not limited to sensing magnetic fields and currents, although this is an excellent demonstration. Any sensor that interfaces via analog, serial, I2C, SPI or digital I/O can be connected to the controller/radio. The only requirement is that the sensors must be very low power so the battery is able to provide a reasonable runtime. Even with this restriction, the device has many potential applications in “smart buildings, ranging from instrumenting the heavy equipment in a machine room to monitoring environmental conditions. The main advantage of the GREEN is that it presents an extremely small, mesh networkable radio platform that is capable of interfacing with a wide variety of input devices.

The future work of this project will focus on the large-scale deployment of this wireless sensor network into buildings to perform condition-based air quality and energy consumption monitoring.

Acknowledgment

The Public Interest Energy Research Program of the California Energy Commission funded the research. The University of the Philippines, ERDT and BCDA-PCIEERD programs provided funds for the first author as part of an expanding research agreement with UC Berkeley. We thank all these organizations for support and many other students and colleagues in the College of Engineering, Berkeley.

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