Demonstration Abstract: Submetering by Synthesizing Side-Channel Sensor Streams

Meghan Clark, Bradford Campbell, and Prabal Dutta
Computer Science and Engineering Division
University of Michigan
Ann Arbor, USA
{mclarkk,bradjc,prabal}@umich.edu

Abstract—
Detailed breakdowns of household energy consumption allow occupants to better understand their energy usage patterns and identify opportunities for energy savings. Current solutions are costly, invasive, and difficult to maintain. Sub-metering approaches rely on—and are hindered by—complex hardware. To address these problems, we demonstrate a sub-metering system that can estimate the power draw of individual loads by augmenting aggregate measurements with very simple sensors. These sensors wake up at a frequency proportional to the power draw of a neighboring load, and report these wakeups to a central server. We model the relationship between each sensor’s wakeup frequency and the load’s power draw as a monotonically increasing polynomial. We calibrate each sensor’s function by constructing a linear least squares problem that allows us to discover the set of polynomial coefficients that minimize the difference between the estimated power draw and the power draw as derived from the aggregate measurements. After calibration, we can convert sensor wakeup frequencies to power draw in real time. This systems approach to sub-metering results in deployments that are easy to install and maintain, allowing users to gain a broad yet detailed view of their energy consumption and costs.

Index Terms—energy-harvesting, power metering, data aggregation

I. INTRODUCTION

Fine-grained, whole-home energy metering is challenging but important: U.S. residential homes consume 38% of all electricity and 22% of the primary energy in the United States [1]. Decomposing the monthly power bill into a detailed, localized report would enable consumers to better understand their usage and reduce waste [2].

Current sub-metering systems suffer from prohibitive device costs, invasive installations, and a lack of scalability due to the complexities of wireless communication. Current approaches attempt to replicate self-contained power metering across the load tree, resulting in hardware-heavy systems that are too costly and unwieldy to provide ubiquitous coverage.

We claim that replicating metering functionality at every node is not necessary to capture the state of the system. By augmenting ground truth aggregate meter readings with hints about how individual loads are behaving, we can algorithmically derive the corresponding power draw. Reducing the sensing requirements for each load monitor so that they only need to provide partial information about power draw allows us to drastically reduce sensor complexity.

Conceptually, we encode information in the ability to send a packet, rather than the content of a packet. A sensor consisting of a radio and an energy-harvester that harvests a side-channel emission of energy consumption (e.g., light, heat, magnetic inductance, vibration) will exhibit a wakeup frequency that is correlated with the power draw of the load to which it is affixed. As individual loads step up and step down, so will the corresponding wakeup frequencies and the aggregate measurements. A central server can use the combination of changing wakeup frequencies and changing aggregate power measurements to automatically calibrate sensors post-installation.

This holistic sub-metering system based on power-proportional sensors contributes effectively zero phantom load and is easy to install and maintain, resulting in ease of deployment and low cost, even for residential building owners.

II. POWER PROPORTIONAL SENSORS

To enable power proportional energy meters, we use a new type of sensor that does not directly measure the power of an AC load, but rather uses a side-channel to indirectly measure the load using energy-harvesting principles. The fundamental idea is that the sensor harvests energy at a rate proportional to the load being measured. Once the sensor has accrued sufficient energy, it wakes up and increments a local counter. On certain wakeups the node also transmits a packet containing the counter value. The central server that receives these packets determines the energy usage of the load based on the sensor wakeup frequency.

We have built several kinds of devices based on this sensing principle, including a plug-load meter (Figure 1a) and a clip-on panel meter (Figure 1b). These sensors harvest energy from the magnetic induction of an active load [3]. Figure 1c shows a solar panel-based light meter [4]. As long as the power draw of the light increases with brightness, we can indirectly estimate its power draw through sensor wakeups.

Each sensor sends a 6LoWPAN packet containing its counter value to a Raspberry Pi border router with a custom TI CC2520-based 802.15.4 radio shield, shown in Figure 1d, which timestamps and routes the packets to the Internet.

III. DISAMBIGUATING LOADS

Aggregate load measurements represent the sum of all the active loads within a building or building subsystem. They
Installation and maintenance costs are kept low.

Real-time load predictions and accurate historical data while their calibration function can be approximated by a strictly increasing polynomial of degree two or less.

Report wakeup counts and satisfy the reasonable constraint that energy-harvesting sensors can be used, so long as the sensors allow our system to be adaptable and to support interoperability. Any combination of heterogeneous or third-party monitors placed at key locations in the "load tree" that frequently characterizes power flow within buildings. However, the resolution of aggregate measurements is too coarse-grained to provide deep insights into the nature of the power draws.

Augmenting aggregate measurements with non-invasive sensors allows us to decompose an aggregate into the individual loads that comprise it. By correlating sensor wakeup rates with changes in the aggregate, we dynamically tune sensor models that enable us to determine individual load profiles. We model the power draw of each load as a function of the sensor wakeup rate, the transpose of Figure 2. Following the work of Kim et al., we call this the calibration function [5]. Based on empirical measurements, we model the dominant characteristics of the sensor calibration functions using a monotonically increasing polynomial of degree two or less. The challenge becomes discovering the coefficients for each sensor’s calibration function that minimizes the error between the sum of the estimated loads and the actual sum of the loads given by the known aggregate. Estimating the coefficients is a linear least squares problem, which we construct using data points representative of load steady-states and solve iteratively until the prediction error is sufficiently small.

This approach can be used to automatically calibrate a sensor even when there is partial coverage of loads. Figure 3 shows that the system was able to correctly calibrate the single active sensor in the presence of three additional uninstrumented loads affecting the aggregate measurements.

Abstracting load power draw as a sensor wakeup frequency allows our system to be adaptable and to support interoperability. Any combination of heterogeneous or third-party energy-harvesting sensors can be used, so long as the sensors report wakeup counts and satisfy the reasonable constraint that their calibration function can be approximated by a strictly monotonically increasing polynomial. The user receives near real-time load predictions and accurate historical data while installation and maintenance costs are kept low.

Fig. 1: Energy-harvesting sensors and 6LoWPAN border router. We have fabricated two form factors of induction-based sensor and one solar-based sensor.

Fig. 2: Wakeup response curve for a plug-load sensor. The more power that is consumed, the more frequently the sensor wakeups occur.

Fig. 3: System performance. The system uses aggregate power to accurately calibrate a single sensor, despite the activities of three uninstrumented loads.

IV. Demo Setup

The demo will consist of a simulated house/single circuit setup. A power strip will represent the circuit and will be plugged into a power meter that will report the total power drawn by all attached devices. Three devices, most likely a lamp, phone charger, and laptop will be plugged into plug-load power meters on the power strip. An additional lamp, which will simulate a ceiling light, will be plugged directly into the power strip with the light powered sensor attached near the bulb. The Raspberry Pi border router will be nearby to receive the packets from the sensors.

A computer display will show what is going on in the system. At the top will be a real time scrolling display showing when new wireless packets arrive from the sensors and the current total load from the power meter. Below that will be real time metrics from the disambiguator showing its power draw estimate for each of the streams. Finally, there will be the ground truth power measurements for individual loads which will update as the load changes. Changing the load will be easy to do by turning on and off lights, connecting or disconnecting a charging phone, and running intensive tasks on the laptop.

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REFERENCES