Low-cost Appliance State Sensing for Energy Disaggregation

Tianji Wu
EE Department
University of California, Los Angeles
i@wutj.info

Mani Srivastava
EE Department & CS Department
University of California, Los Angeles
mbs@ucla.edu

Abstract
Reliable detection of appliance state change is a barrier to the scalability of Non Intrusive Load Monitoring (NILM) beyond a small number of sufficiently distinct and large loads. We advocate a hybrid approach where a NILM algorithm is assisted by ultra-low-cost outlet-level sensors optimized for detecting appliance state change and communicating the event on a best-effort basis to a central entity for opportunistic fusion with the state change detection mechanism within NILM. In support of such an approach we present the implementation of an appliance power state sensor which achieves low cost via design choices such as a transmit-only radio. We also present results from a study where the sensors tracked power states of tens of appliances with high accuracy.

Categories and Subject Descriptors
H.4 [Information Systems Applications]: Miscellaneous; B.0 [Hardware]: General

General Terms
DESIGN

Keywords
Sensor; Appliance state change; Energy disaggregation.

1 Introduction
Research studies in recent years have indicated that providing timely and disaggregated energy consumption feedback to people can help them in conserving energy [2]. Two categories of solutions have emerged for sensing disaggregated energy consumption. At one extreme is the approach of using networked sensors directly measuring energy consumption at end points, providing high fidelity but also incurring high hardware, installation, and management costs. At the other extreme is Non Intrusive Load Monitoring (NILM) where current and voltage signals at the central meter are analyzed to deduce changes in appliance activity states and apportion energy consumption. A common approach in NILM is to rely on steady states [3]. More sophisticated NILM methods [1] use transient signatures during power states change to identify appliances. While it is economical with no additional sensors needed, NILM usually works well only when the loads are few (typically no more than 6-7), sufficiently large, and have distinctive signatures. Moreover, better performing NILM approaches make use of high frequency spectral features, thus requiring costly high-rate samplers and wide-band current transformers.

A hybrid approach where additional sensors assist NILM can help remedy the scalability problem. We have explored an approach where networked sensors deployed at outlets into which appliances are plugged in to provide the NILM algorithm with state change events. The sensors thus assist the NILM algorithm in what is probably the root cause of lack of scalability in NILM: the inability to accurately detect appliance state changes when there are a large number of appliances of similar types with small current consumption. Since the sensors are meant to detect and communicate only binary on-off state changes, it was our hypothesis that they could be designed at very low cost. This paper describes our work in designing a very-low-cost sensor node optimized for sensing and transmitting the binary on-off state of an appliance attached onto it. We show that with such under-designed sensors, the cost can be lowered into an acceptable range for large-scale deployment, and yet they provide much crucial information for energy disaggregation by NILM.

Related work includes ViridiScope [5], which uses several kinds of sensors to tell the on-off states of appliances (assuming all appliances have binary states). These sensors include light sensors, sound sensors and magnetometers. With the knowledge of the states of all appliances and the aggregated power readings over time, researchers can calibrate how much power each appliance consumes using linear programming. Philosophically, our work takes the opposite approach to ViridiScope: in ViridiScope the central meter assists in calibrating the distributed sensors to relate the sensor signal to appliances power consumption, whereas in our system the distributed sensors assist the disaggregation algorithm at the central meter by providing appliance state change information. In another related work [4], the authors automatically identify where to install sub-meters in order to achieve satisfactory disaggregation accuracy, but assume availability of reliable on-off state information of all
appliances, which is actually the purpose of our work. Finally, prior research [5, 6] has explored contact-less sensing of appliance state transitions by detecting side-band signals such as sound, light, and electromagnetic fields. While it can be less disruptive, contact-less sensing is higher cost due to the increased complexity of a power supply requiring battery or some form of energy harvesting.

2 Low-cost sensor for tracking power state

2.1 Hardware design and state sensing

We designed the state sensing sensor to plug into an AC outlet, and provide a pass-through AC outlet for the appliance. Internally, the hardware senses the current flow to determine the on-off state of the appliance, and reports to a base station wirelessly. Fig.1 shows a block diagram of the hardware. The sensing subsystem is designed to consider an appliance to be off when it is in the lowest possible standby mode, and to be on when it is in any power state higher than the off state. Available commercial and research sensors are designed to measure and communicate power consumption, and thus acquire both voltage and current signals at a high enough rate for subsequent multiplication and integration to compute the real power consumption. The calculation of the real power waveform is usually done in a metering chip or a dedicated module integrated in a microcontroller unit (MCU) before being sent to a radio of adequate data rate. While such power metering sensors can be used to detect appliance on and off states, a sensor node specialized for state detection can be of much lower complexity and cost. Based on the observation that appliances of interest all had off-state power consumption lower than 10W, and the lowest on-state consumption much higher than 10W, we designed the hardware to sample only the current signal, and used simple thresholding for state classification and transition detection. This considerably simplifies the circuit, and eliminates the need for dedicated metering chip or module. Our design uses a very low-end MCU, the ATTiny10, which is a miniature MCU with just 6 pins in total, including 4 GPIO pins. It has an ADC which we used to sample the current waveform. A 1mΩ resistor in series with the appliance captures the instantaneous current flow. The voltage drop across the resistor is amplified 100 times and sampled by the MCU. The MCU obtains the range of the instantaneous signal, which represents the magnitude of current, classifies it into on or off via thresholding with hysteresis, and performs a debouncing algorithm to compute the on-off state value of the appliance.

2.2 Transmit-only radio communication

The specialized nature of the sensor also enables considerable simplification of the radio communication as well. Based on the realization that appliance power state change events are very sparse in time and across appliances, and that small losses in state change event reports are algorithmically tolerable, we made the decision to reduce hardware complexity by adopting a transmit only design with a very low-end 315MHz radio transmitter, single hop communication, and redundant packet transmission to minimize impact of packet loss. While there are many mature radio solutions used in sensor networks, such as IEEE 802.15.4, ANT or Bluetooth, they target high data rate and bi-directional information exchange. For our application, their main drawback is high cost, not only because of the costlier radio chips, but also because of the need for a more sophisticated MCU that can communicate with the radio chip. The bare-minimum transmitter we use needs only one digital pin. We also explored power-line communication, but did not choose it because the link quality is no better than wireless in cluttered electrical environments, and the components to couple data signal to the power-line are big and costly.

Since the transmit-only design precludes ARQ based retransmission of event reports that are lost due to noise or collision, we adopt a redundant retransmission strategy whereby an event report is sent five times with non-uniform spacing, and successful reception of any one of them is sufficient. To further improve the probability of success, the sensors synchronize their transmissions to AC cycles, using a simple zero-crossing detection circuitry. When an event is detected, an initial transmission of the event begins on the next AC cycle, followed by 31 retransmission time-slots. These time-slots are in 4 groups. The node randomly picks one slot from each group. Altogether there are 32 time-slots, or 128 AC cycles (each time-slot is 4 AC cycles), which is roughly 2.2 seconds long. The group number and time-slot number are embedded in the packets so that the base station can estimate the delay from event occurrence to event report reception.

2.3 Cost and scalability analysis

Various design choices we made collectively result in low-cost. By sensing the current instead of power, we eliminated the need for a metering IC or an MCU with meter module. Because only binary state output is needed, distortion and clippings are tolerable during signal capture and processing. Thus, we do not need to calibrate the analog front-end amplifiers. By employing a bare-minimum RF transmitter module, we eliminate the need for a complete RF IC and an MCU with SPI or other interfaces. Thus with no need for any peripherals other one analog input and two digital IOs, we were able to choose a really low-end MCU. Moreover, the functions of the MCU are 1) taking threshold and smooth it, and 2) toggle a pin for RF transmission. The first can be done with pure analog circuitry, while the latter can be replaced by a sequence generator circuitry. Hence, it is even possible to replace the MCU with a very simple customized IC, which would be more cost-effective at large quantities. To package our prototype sensors for deployment, we reused the plastic packaging of a commercial plug-load timer. While the physical size is limited by the packaging, the circuit board

![Figure 1. Block diagram of the on-off state sensor hardware (a) and photo of the sensor prototype (b)](image-url)
itself can be made much smaller so as to be embeddable in AC plugs and outlets. The unit cost of components and board fabrication and assembly is less than $2 at a quantity of 1000.

3 Evaluation

For evaluation we first set up a testbed with a network of our sensor with the ability of programmatically injecting synthetic appliance state change events at various sensors to help stress test the reliability of the transmit-only approach we adopted with different density of events. Each sensor receives the synthetic events from an external mbed (http://mbed.org/) module, with the various mbed modules under the control of a script in a central computer. The sensors run a slightly modified version of firmware, which enables them to receive events from the digital input pin, instead of using the AC current step detection. Nevertheless, the AC current step detection algorithms are still running in order to emulate the timing of event detection as accurate as possible. The RF transmission software is unmodified. The sensors are plugged into AC sockets and powered by AC, so that the zero-crossing function is also working in the same way as it would in real deployment. At each node in a six-node configuration we independently issued a series of Poisson distributed events. The average interval of events is $\mu$ seconds. Fig.2 shows the packet delivery rate (PDR) and event delivery rate (EDR) with different $\mu$. When $\mu > 15$, EDR is almost perfect. In real settings, $\mu$ is much greater, since most appliances are unlikely to toggle so frequently.

For further evaluation we deployed a 20-sensor system in our 1000 sq. ft. laboratory space with about a dozen permanent occupants, a dedicated electrical panel, and an electrically cluttered environment with many dozens of diverse electrical devices such as computers, instruments etc. We arranged the twenty appliances under study (9 LCD monitors, 8 laptop computers, a solder station, a workbench light and a water dispenser) to be on four branch circuits to avoid interference from other appliances in the lab. Most appliances are binary-state, except the water dispenser, which has both a cooler and a heater, but they work independently as if they were two separate appliances. We instrumented 11 of the appliances with networked Watts up? PRO meters to capture the ground truth. The results we report are based on a 7-day long section of our dataset, from June 1st-7th, 2012. We use power state change events detected by our sensors to reconstruct the states of each individual appliance over time, and compare it with a power state trace computed from the ground truth data via thresholding. We measure accuracy by precision (the ratio of the time an appliance was both actually on and reported to be on to the time it was reported to be on) and recall (ratio of time an appliance was both actually on and reported to be on to the time it was actually on). Our data show that both precision and recall of all appliances we monitored were greater than 99.7%, indicating reliable and accurate tracking of appliance state. While the focus of the present short paper is on the sensor design itself, we also quantified the impact that our system would have on the NILM performance. We compared the relative performance of the two appliance power state tracking approaches: estimated from aggregate power trace using change detection as a pure NILM system would do vs. using reports from our sensors. Over the 7-day period, the change detection using the aggregate trace and a representative algorithm for detecting step changes in the power trace failed to detect 8.3% of the events, reported nearly 68% false state changes, and did not associate the state change with appliance id. Additional details on the impact of our sensing system on the performance of NILM are described in [7].

4 Conclusions and Acknowledgements

We advocate addressing the lack of scalability in current NILM approaches by moving to a hybrid approach where minimal supplementary information relating to appliance state change is provided by a network of sensors. Unlike direct sensors of appliance power, the state change detection sensors can be made much simpler and lower in cost using extremely simple MCU, an uncalibrated sensing frontend, and low-bandwidth transmit-only radio. These characteristics make the sensors suited for large-scale deployment where they may be embedded in every outlet and power strip, or perhaps be built into the appliance. Our work shows that such a sensing system can reliably track power states of tens of appliances, thus enabling robust energy disaggregation.

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5 References