The Design and Evaluation of an End-User-Deployable, Whole House, Contactless Power Consumption Sensor

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ABSTRACT
We present the design, development, and evaluation of an end-user installable, whole house power consumption sensing system capable of gathering accurate real-time power use that does not require installing a current transformer around the electrical feeds in a home. Rather, our sensor system offers contactless operation by simply placing it on the outside of the breaker panel in a home. Although there are a number of existing commercial systems for gathering energy use in a home, almost none can easily and safely be installed by a homeowner (especially for homes in the U.S.). Our approach leverages advances in magnetoresistive materials and circuit design to allow contactless operation by reliably sensing the magnetic field induced by the 60 Hz current and a closed loop circuit allows us to precisely infer the power consumption in real-time. The contribution of this work is an enabling technology for researchers in the fields of Ubiquitous Computing and Human-Computer Interaction wanting to conduct practical large-scale deployments of end-user-deployable energy monitoring applications. We discuss the technical details, the iterative design, and end-user evaluations of our sensing approach.

Author Keywords
Ubiquitous computing, energy monitoring, sustainability, sensing, smart home

ACM Classification Keywords
H5.m. Information interfaces and presentation (*e.g.*, HCI): Miscellaneous.

General Terms
Design, Measurement, Performance

INTRODUCTION AND MOTIVATION
Human activities relating to home energy use in the home are directly responsible for 28% of U.S. energy consumption [14]. Most people, however, are unaware of how their daily activities impact the environment or how often they engage in those activities. Feedback has been shown to be one of the most effective strategies in reducing electricity usage in the home [5, 7, 16]. Thus, with the advent of new sensing technologies, we now have the potential to provide personal, relevant feedback in real-time for a variety of consumption activities.

Figure 1: Left: Contactless, whole house power consumption sensor. The sensor can be adjusted to accommodate most electrical breaker panels. Right: Sensor installed on the outside of the breaker panel.

Many researchers in the Ubiquitous Computing and Human-Computer Interaction communities have seized the opportunity to explore a variety of applications for helping individuals reduce their overall energy use [3, 4, 8]. One particularly important piece of information is real-time, whole house power use, which can be obtained using one of a number of commercially available accurate real-time current sensors. However, these sensors typically require professional installation to provide an acceptable level of safety because the sensors are installed around the hot power feeds coming into the home in the circuit breaker box (particularly in the U.S.). As we have found, most users are neither trained nor confident that they could accomplish this installation on their own.

We have built an accurate, whole-house, contactless power consumption sensor (CPCS) that greatly reduces the deployment burden of installing such systems and enables widespread exploration of electricity monitoring applications by allowing potential end-users to install the sensor (see Figure 1).

Our approach leverages new advances in magneto-resistive materials and circuit design to allow contactless operation. The CPCS senses the magnetic field induced by the 60 Hz current and a closed loop circuit that allows us to precisely infer the current consumption in real-time. These sensors can also be used to determine the power consumption of individual devices that do not have easy access to their power feeds (*e.g*., electric water heater, central heater, *etc.*). Our system consists of two easy-to-install units. The first is a sensor unit placed on the electrical breaker panel (see Figure 1) and the second is a simple plug-in device installed in any electrical outlet in the home. The sensor unit on the breaker panel detects the household current draw from the magnetic field generated from the 60 Hz current flow, while the plug-in module briefly pulses a series of known load for automatic initial calibration as well as sensing the line voltage for calculating true power.

We present the design, development, and evaluation of our end-user deployable, whole house power consumption sensor. This paper seeks to share a novel technology with an eye towards design considerations for its practical use. In this paper, we first discuss the related work and the difference between our approach and existing approaches as well as past work in evaluating end-user deployable sensing systems. We then describe the theory of operation and the implementation details. We next share the performance analysis of our system to show its accuracy compared to a traditional transformer-based sensor. Finally, we discuss our surveys, user evaluations, interviews, and participatory design sessions we conducted. These were aimed to show the need for our sensing system, elicit people's understanding about the installation process, understand their ability to install the system, and solicit feedback on the technology and installation procedure.

RELATED WORK

There are a number of commercial electrical sensors available. The least costly devices, such as Kill-A-Watt™ and Watts Up™, simply measure the energy used at a single outlet and display the data on the device. The two most popular and inexpensive whole house sensing systems are The Energy Detective (TED®) and the PowerCost Monitor. TED uses a transformer-based current sensor installed inside the home's main circuit breaker panel, while PowerCost uses a sensor attached to the face of the home's power meter. Both offer a variety of display modes from current energy consumption in kW or dollars to energy consumed each day or since the last energy cycle. Others have used magneto sensors directly on a wire to infer power consumption [12]. PowerCost is the easiest to deploy and can be installed by a homeowner, however, it relies on electromechanical meters and electronic meters with an exposed optical port. Thus, this solution is constrained to specific types of meters and may not be suitable for apartments, where the power meter might not be easily accessible. The variance in the integration scheme used by typical power meters limits the resolution and the time interval of the data. Finally, "smart meters" typical only provide interval data (*i.e*., 15 minutes), vary across manufactures, and are not currently easy for researchers to obtain data from them. Our solution is very flexible, provides real-time data, and can be used in any home *now* where there is a breaker panel for the living space, which is required by national electrical codes.

Although some of these existing solutions show some promise, they have the following drawbacks:

- Inline sensors **only work well for an appliance that has a modular plug,** and there needs to be a sensor installed for every device of interest.
- Closed loop transformers that allow a device to be clamped around an electrical wire **require an appliance's power feed** to be easily accessible.
- **Safely installing a whole-house current sensor requires hiring a trained electrician** because it involves placing a sensor around the main electrical feed in the breaker panel.

Attempts at cost-effective energy monitoring date back to the early 90's, with research attempting to classify appliance usage by monitoring electrical current consumption [2, 6, 9, 10]. More recently, researchers have also monitored current flow to infer the appliances or electrical equipment being used in the house [9, 15]. Our solution can provide both real-time current information as well as current harmonic data (up to 1 MHz) needed for activity recognition applications. We can envision this device supporting many of the applications already presented in prior literature with the added value of being easy-to-deploy. Our system also provides the necessary data needed for assigning power consumption to each appliance or device for electrical disambiguation systems, such as the system by Patel *et al*. [13].

Researchers have shown that feedback provides a basic mechanism with which to monitor and compare behavior and allows an individual to better evaluate their performance. Feedback technologies have also been shown to be one of the most effective strategies in reducing energy consumption in the home [5]. Fischer reviewed over twenty studies from 1987 exploring the effects of feedback on electricity consumption [7]. She found that typical energy savings were between 5% and 12%. In a similar review of thirty-eight feedback studies carried out over a period of 25 years, Darby found typical energy savings of 10-15% [5]. Solutions that worked well provided computerized feedback with multiple feedback options and views, were updated frequently, allowed the user to inspect the data closely, and were capable of providing detailed, appliance-level energy usage. One of the major deficiencies in the current literature is that few have studied the underlying cause of behavior change influenced by feedback technology nor its long-term impact. Part of this has been the limited number of sensors and tools available for researchers to conduct these large-scale studies. Many of the past studies involved painstaking sensor installations. Our research aims to obtain accurate data from easy-to-deploy sensing designed to be installed by end-users.

Researchers have also looked at the acceptance of sensors in the home as well as end-user deployment considerations, which provides us with some guidelines for designing our solution. Hirsch *et al.* examine the social and psychological factors that influence the design of elder care sensing systems and applications [11]. Among their findings is a concern that assistive technology may be rejected if it detracts from the aesthetics of the home.

Beckmann *et al.* present a study of end-user sensor installation and reaction to sensors in the home [3]. They had end-users install vibration sensors, in-line electricity monitoring sensors, motion detectors, cameras, and microphones. They found that end-users made a variety of errors, often due to the directional requirements of sensors or uncertainty over exactly where a sensor needs to be positioned. They also found many negative reactions to the intrusion of sensors into the living space, including objections to the potential for damage caused by the adhesive used for installation, concerns that sensors were placed in locations accessible by children or pets, and objections to the placement of cameras and microphones in the home. We use some of these principles in the design of our system in addition to offering new insights in building end-user deployable sensing systems.

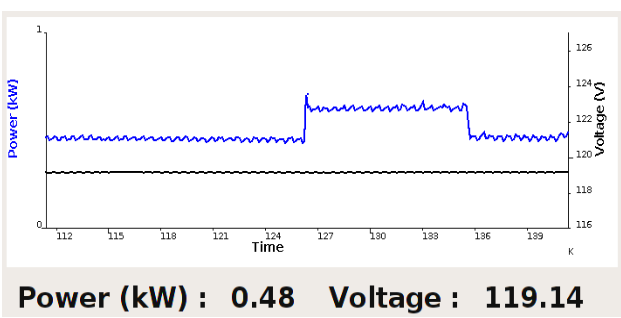

Figure 2: Simple real-time power consumption interface showing whole house power data from our sensor.

CONTACTLESS POWER CONSUMPTION SENSING

Overview of the Technology and its Design

The design and development of our contactless power sensor was based on an iterative design process with homeowners interested in monitoring their home's power consumption, who had a particular interest in a device that did not entail the cost of professional installation. We recruited two individuals to help us with the design of the system and solicit feedback on what they would find acceptable for its installation. We presented designs to them at various points throughout the process to help inform the construction and the technical requirements for the CPCS.

We settled on a design for the CPCS system, which consists of two devices. The first is a sensor unit placed on the electrical breaker panel in a home (see Figure 1) and the second is a simple plug-in device installed in an electrical outlet in the home. The sensor unit on the breaker panel detects the household current draw from the magnetic field generated from the 60 Hz current flow, while the plug-in module briefly pulses a series of known loads for automatic calibration as well as sensing the line voltage for calculating true power. The automatic calibration was a key element in the design. Figure 2 shows a simple power interface and Figure 3 shows the overall system diagram.

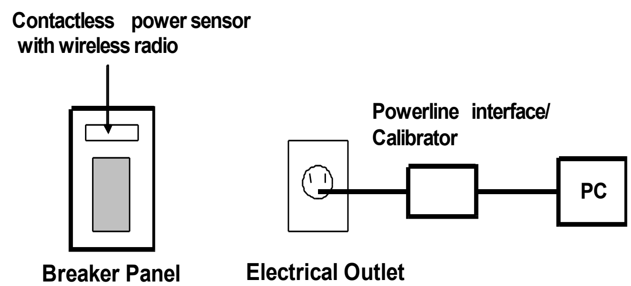

Figure 3: Block diagram of the various components of our system. The PC computes the actual power consumption and could be implemented as an embedded computer with a display depending on the application.

The ideal placement for the sensor units is directly over the lugs that connect the electrical feeds to the breaker panel's bus bar (see Figures 4 and 5). Ideally, the user would remove the main panel from the box to locate this exact position, but this would compromise the safe installation of this device. Rather, the sensor unit provides feedback through 2 LEDs that helps the user search for this location by hovering it over the breaker panel (akin to a wall stud finder). We can assist the user in finding the ideal spot by using a set of heuristics derived from the standards used in the design of breaker panels.

Breaker panels in the U.S. comply with the General Electric "style," which is based on the National Electrical Manufacturers Association (NEMA) and National Electric Code (NEC) guidelines. The dead frame and trim are the front surfaces of the breaker panel that cover the interior (see Figure 5). The trim includes an access door. NEMA has established guidelines for electrical equipment enclosures including breaker panels. In particular, according to NEMA, the bus bar must be arranged either vertically or horizontally with the line's connection lug residing at the end of the bus (see Figure 5). Figure 4 shows the rough locations where the ideal position would be for the CPCS. The directions the breakers flip is a good indicator for whether the electrical feeds occur on the top/bottom or left/right.

The ends of the CPCS are lined up with the ends of the circuit breakers (see Figure 1). When the user is near a suitable location (based on the received 60 Hz signal) with the sensor, one or both of the LEDs will begin to flash. The LED becomes solid if that section of the sensor unit is above an acceptable location with sufficient AC signal. The goal is to have both LEDs solidly lit, which indicates both internal sensors are effectively picking up the two current carrying legs (see Theory of Operation section). The sensor unit has the ability to be expanded by simply sliding it apart to accommodate older or non-standard breaker panels that do not conform to the NEMA standard. Typically, for standard breaker panels, the user would only have to move the device as a unit. A strategy for finding a suitable placement is to place to over a candidate location and try to get one LED solidly lit first. Then the user can move it left and right or slightly rotate it to get the second LED lit. If the user is unable to get both LEDs lit simultaneously, the sensor can be adjusted by moving the two halves in and out.

The sensor unit adheres to the breaker panel using a thin adhesive, such as double sided tape (we use 3M™ Command-it Foam Tape). Prior to mounting the device, the user just needs to confirm that both indicator LEDs are solid. Although our prototype is wireless, it still requires to be plugged into the nearby outlet for power. In the future we can imagine making the CPCS battery-powered.

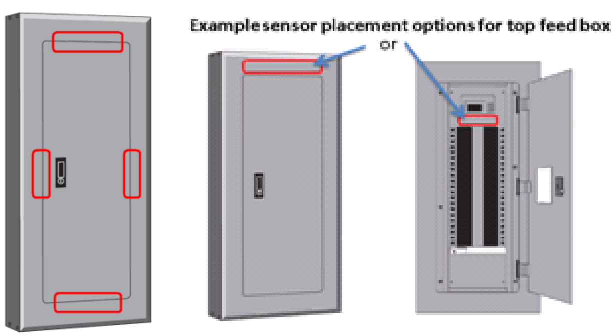

Figure 4: Left: Example locations for optimal sensor placement depending on where the electrical mains connect to the bus bar (top, left, right, or bottom). Top/Bottom and Left/Right can be determined by looking at alignment of the breakers (horizontal = Top/Bottom and vertical = Left/Right).

Theory of Operation

Our sensing approach involves computing the power consumption in the home by inferring the current being drawn through the main lines coming in the home at the breaker panel. Since most homes in the U.S. have split, two-phase electrical service, we need to detect the current at both legs. Standards in breaker size and code guidelines provide some structure to how the electrical feeds connect to the lugs on the bus bar in the breaker panel (see Figure 5). For example, the wires for the two electrical phases come in parallel to each other when connected to the bus bar. The field generated from the two legs or phases allows us to estimate the current flow through each leg separately, which radiates a few centimeters from the wire and even through the layer of sheet metal.

The CPCS operates using an anisotropic magnetoresistive (AMR) effect, which is a change in the resistance of ferromagnetic materials from a changing magnetic field. An AMR sensor element is composed of nickel iron alloy deposited as a thin film on a silicon substrate. Four such elements are arranged as a Wheatstone bridge. A constant current is applied to the bridge, and in response to an applied magnetic field, two elements increase their resistance and two elements decrease their resistance. This results in a voltage change at the bridge output.

Magnetoresistive (MR) sensing offer advantages over other magnetic sensing technologies. Compared to current transformers or inductive-based solutions, MR sensors are smaller, lighter, and have wider bandwidth and greater dynamic range. A large dynamic range enables the measurement of small changes in a large current (*e.g.,* detecting when a night light is switched on while the HVAC system is running). MR sensors are more sensitive than Hall Effect sensors and can be deployed at some distance from a current-carrying wire. Although fluxgate sensors are more sensitive than MR sensors, their support circuitry is more complex, and they typically do not deliver truly continuous measurements.

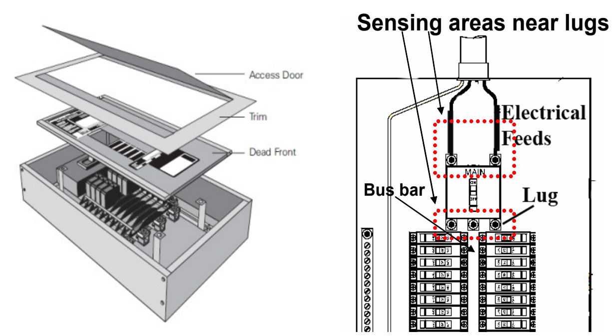

Figure 5: U.S breaker panel components. Our sensor can be installed on either the trim or on the dead frame under the access door as long as it is over the highlighted areas.

Implementation Details

Hardware

We use the Honeywell HMC1022, which contains two sensor dies placed at right angles in a 16 pin SOIC package. Sensitivity is greatest to magnetic fields normal to the sensor plane and aligned along the X axis (die A) or Y axis (die B). Identical circuits support each die. The two axes allow us to electronically gimble the sensor with respect to a plane to reduce orientation effects. However, since the sensor is designed to sit on a flat surface with the electrical feed or bus bar residing underneath the sensor, we found that one die placed to capture the outward field is sufficient. The circuit for a single die is shown in Figure 6. We use two HMC1022 sensors, one for each electrical leg.

The sensor operates in a closed loop configuration to achieve high linearity and dynamic range. The sensor bridge output is fed to an OPA228 operational amplifier,

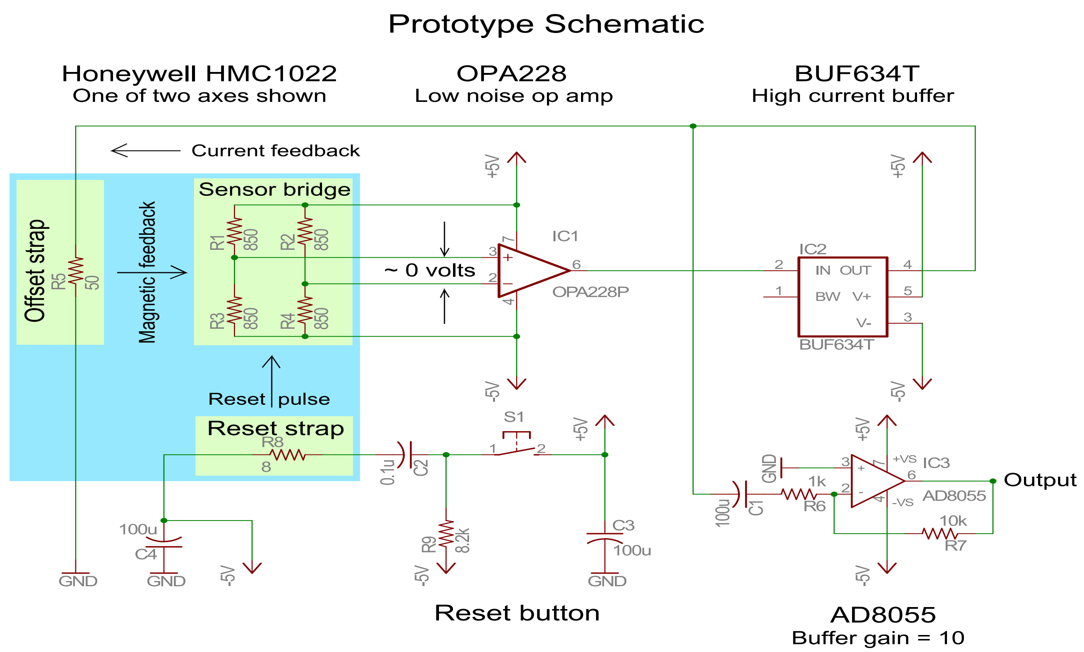

Figure 6: Schematic of the drive circuitry for each sensor in our contactless, whole-house, power consumption sensor unit.

which has low input offset voltage, low noise, and a 33 MHz small signal gain bandwidth product. The OPA228 is designed to drive relatively high impedance loads, so a BUF634 boosts signal current for driving the 50 ohm offset strap. The feedback loop formed by the sensor bridge, amplifiers, and offset strap works to maintain zero voltage between the OPA228 input terminals. Hence, it maintains a zero magnetic field at the sensor bridge, where its linearity is greatest. Current flowing through the offset strap is converted to a voltage by offset strap resistance, and this voltage is amplified for output by an AD8055 low noise, 300 MHz operational amplifier.

The reset strap exists to maintain sensor bridge performance by correctly aligning the magnetic domains within the bridge elements. The domains become misaligned when subjected to strong magnetic fields, such as those from a permanent magnet or those generated by the offset strap while the circuit powers up. As a result, the bridge becomes less sensitive and responds with less linearity to applied magnetic fields. The reset circuit is used after power up to apply a brief pulse of high current to the reset strap, which restores proper alignment of the domains and is periodically applied to “degauss” the sensor.

The schematic shows a bipolar power supply and omits supply decoupling capacitors for clarity. The prototype circuit was constructed using a 12 V unipolar power supply, with virtual grounds for the offset strap furnished by LM7171 operational amplifiers. The frequency response is more than adequate for sensing powerline current. The extra bandwidth allows for more sophisticated classification of events on the powerline [9, 10, 13].

The outputs of the two sensors are connected to a 16-bit Texas Instruments ADS8344 ADC and AVR microcontroller. The microcontroller is connected to a Class 1 Bluetooth radio implementing the serial port profile and also drives the feedback LEDs. We can reliably sample and stream the sensor data over the Bluetooth channel at 1 kHz, which is sufficient for sampling the 60 Hz cycle. It is even possible to use a standard sound card to sample and analyze the sensor data. The entire CPCS is powered by an AC power adaptor, but we can imagine building a battery operated version in the future.

In order to associate the raw sensed current with consumed power, we constructed a plug-in device (called our calibrator) which cycles through a series of known loads (10 W→50 W→100 W→200 W) that are pulsed at 1 Hz. Our calibrator is constructed using a microcontroller and a relay driver that switches in one of the four loads resistive loads. For our prototype, these are simply mini-halogen or incandescent bulbs, but a deployable version could easily be built with power resistors. The plug-in device also monitors the line voltage (through the microcontrollers ADC), which is necessary for calculating the true power. Note that we technically need the line voltage for each phase, which can be obtained by monitoring two different electrical outlets or monitoring a single 240 V outlet. However, we have found that it is sufficient to just monitor one leg since the line voltages are similar in residential power systems and the two phases are typically 180 degrees out of phase. This simplifies the install by the end-user.

Software

For our prototype, the calibrator is connected to a PC through a USB connection. The PC also calculates the power consumption (through an application written in C) and provides the real-time power interface (Java GUI application). Signal conditioning and processing is accomplished using the GNU Radio software toolkit. The sensor data is streamed to the Bluetooth-enabled PC at approximately 1 kHz.

After passing the data through a low-pass filter to help isolate the 60 Hz cycle, we first compute the root mean square (RMS) of the AC sinusoid for each electrical leg's sensor. The total current consumption (in raw signal space) is computed by summing the RMS values of the two phase signals. A correction factor is applied to map the raw RMS value to the actual total current using the calibrator. Observing four subsequent raw signal values of increasing magnitude allows us to associate the respective values of the known loads. The step change in the raw signal space is correlated to the calculated current draw of the known load (using the line voltage). This is computed for each of the fours known states of the calibrator. Five samples of each are taken and then average before computing the linear function. The function provides the necessary $Irms$. Finally, we then calculate the average power as follows: $Pavg=Vrms \times Irms$, where $Vrms$ is derived from the line voltage.

SENSOR PERFORMANCE EVALUATION

We conducted experiments in three different homes (two single family homes (built in 2003 and 1954) and one apartment home (built in 1960) to evaluate the performance of the CPCS. The experiments were conducted using a combination of a variety of electrical appliances and devices found in each home (lights, stove, fans, TVs, *etc*.). We installed a commercially available transformer-based (GE split core) power meter, typically used for sub metering applications inside the breaker panel prior to installing our sensor on the outside of the breaker panel for obtaining ground truth. The transformer is factory calibrated and has an accuracy of about 1% up 100 A.

After installing and calibrating our current sensor, we observed the whole house power consumption using the ground truth sensor. We operated a random combination of household devices on both legs to obtain aggregate household power draws ranging between from 50 W – 3000 W at roughly 50-100 W increments from 50 W – 1000 W and 1000 W increments above 1000 W. At each increment, we noted the value reported by the ground truth sensor and our CPCS. During data collection, we made sure to operate different types of loads (resistive, inductive, *etc*.).

Using the ground truth sensor as the reference, we calculated the percent error of our sensor for each noted power consumption data point. We gathered approximately 15 data points across the 50 W – 3000 W window for each home. Figure 7 shows the average error of the CPCS across all three homes at various consumption levels. We yielded an average error of 4.90% when compared to the ground truth sensor. Closer inspection shows that the accuracy drops near 1000 Watts of total load. For aggregate loads of less than 1000 W, the error was 3.75%. This is attributed to the fact that our calibrator had a maximum test load of 200W, thus creating a linear function that did not model the higher loads very well. Figure 7 also shows the improvement in the accuracy after including an additional 1000 W calibration point for computing the linear function. The average error dropped to 4.29%.

Although the performance of the high aggregate loads improved, there was a slight decrease in performance for the smaller loads, resulting from the change in the slope of the linear model. Even at roughly 4%, these are very encouraging and acceptable numbers when considering the accuracy of consumer whole-house energy monitoring devices are also around 4%. The performance can be improved a little by using a higher order monotonically increasing polynomial model, but the major source of error is that we only calibrate the sensor at one of the two phases. Slight differences in the two sensors and differences in the location of the main feeds under the sensor would account for a significant portion of this error. After calibrating the sensor on both phases (by installing the calibrator in two different outlets that were on separate legs), the average errors dropped to 2.74%. This poses an interesting tradeoff between the ease-of-installation and the accuracy of the system, which we revisit later.

To assess long-term stability and evaluate the potential change in calibration, we left the sensor installed for over a month in one home. Even after four weeks without re-calibrating the sensor, we did not notice any noticeable drift (average error of 3.9% during the first day vs. 4.2% after a month). Any minor changes could have been attributed to the adhesive causing the contactless current sensor shifting due to changes in temperature. The calibrator could easily be designed to periodically update the model to mitigate potential calibration drift problems.

Finally, we wanted to evaluate the effective practical resolution of the CPCS. By turning off the breakers to most of the appliances in the home, as not interrupt the experiment with background devices automatically actuating, we determined that the smallest discernable current draw is about 100 mA, which we generated through powering a set of LEDs through a plugged in regulated power supply. The theoretical dynamic range of our sensor (assuming the offset strap runs at 20 gauss) is over 100 A. The effective dynamic range and resolution is clearly dependent on the connected ADC, but it is important to note that our approach is capable of detecting both low and high electrical loads.

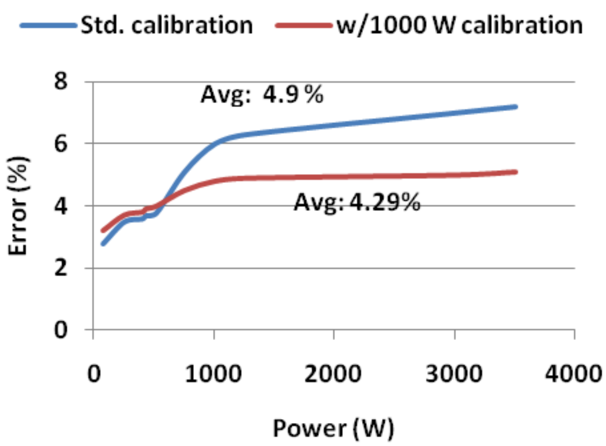

Figure 7: Average error in percent of our sensor with respect to a commercially available current transformer-based power meter. Both the standard calibration sequence and the calibration sequence including a 1000 W load are shown.

USER EVALUATION METHODS

Having designed and developed a working prototype, we wanted to evaluate the effectiveness of this technology as an end-user-deployable solution. Although the participatory design sessions contributed significantly to the design of this solution, it was still limited to two individuals. Thus, we wanted to solicit feedback both about the technology and its installation process from other users. In this section, we describe two user studies we conducted. The first was an online survey to assess the comfort levels and willingness of individuals to use a technology that requires them to install something on the outside of their breaker panel. The second is a user evaluation of individuals actually installing the device in their home, which consisted of an observation of the installation procedure followed by a semi-structured interview.

Installation Comfort Survey

We first wanted to evaluate the perceived comfort level of an average U.S home occupant installing the CPCS and a traditional transformer-based current consumption device, like the TED. These traditional transformer-based devices typically require the removal of the entire cover of the breaker panel and installation of the sensors around the two electrical lines connecting to the bus bar. Clearly, there are safety concerns associated with an inexperienced individual attempting this installation. Thus, one could infer that a contactless sensor would hold more appeal, because of its easier installation. However, for completeness, we wanted to quantify users' comfort levels for each of these two approaches. In addition, a question still remained if a perceived discomfort with modifying their main electrical panel would still remain even if we were to introduce our new approach.

An online survey that described both technologies and their installation procedures as well as the basic idea of real-time power monitoring for a home was deployed. The participants were asked to rate their level of comfort with installing each device on a Likert scale from 1 to 5 (1 being not comfortable at all and 5 being very comfortable). In addition to the standard demographic information, we asked participants if they would be interested in an energy feedback system and how much they would pay for it to be professionally installed. Among other questions, we also provided them with the ability to explain each one of their answers if they so wished.

We attempted to control for ordering bias by randomly alternating which technology we presented first in the survey, which yielded each technology being presented first approximately half of the time. We deployed a link to the survey via email outside of the research group. For recruitment, we used a snowball sampling approach with individuals forwarding the survey on to their own extended family and social networks. Care was taken not to deploy the survey to the direct acquaintances of members of the research group as to get a diverse set of participants.

End-User Installation Evaluation

The aim of the user evaluation was to actually have potential users try to install the device in their home. In the survey, we asked participants to list their contact information if they would be interested in further helping evaluate our power consumption sensor by having them attempt to install it in their home. Participants for this study were limited those that lived in the immediate geographic region of the research lab. We used the demographic information to help select a diverse set of participants. The intent of the evaluation was to gather some initial insights across a variety of demographics and expertise levels. We recruited a total of 8 participants, all of which had selected a 4 or 5 for their comfort level for installing the CPCS.

Note that because of safety considerations with current transformer-based solutions and the manufacturer's recommendation of professional installation, we were unable to evaluate the ability of participants to install those types of devices. Rather, the aim of the evaluation for our sensor was to determine whether users are able to successfully install the device in their home and uncover challenges with its installation.

During our visit, each participant was first given a two-page instruction manual. After reviewing the manual, they were asked to install the sensor in their home. We observed their installation, but did not help them with its placement of the sensor. The participants were told that we were evaluating the usability of the device and that we would be soliciting their feedback about the install and potential improvements to the system. In the unlikely event the researcher were to observe a dangerous action being taken by the installer, the researcher was obviously instructed to intervene.

We defined a successful installation when users were able to accurately see the power consumption of two known loads on the feedback interface. For example, most homeowners selected an incandescent lamp and a television, where the power draws were determined with an inline power meter we provided. If they were able to see the change in power for their selected devices within an 8% error range during its operation, we concluded they had successfully installed the CPCS.

Immediately following the observation of their installation, we conducted a semi-structured interview with the participants. We asked them to reflect on the installation procedure, challenges they faced, and provide advice on improving the design of the sensor unit.

Table 1: Summary of participants that completed the online survey.

Number of Survey Participants	73
Gender of Participants	Male (43%), Female (57%)
Ages	18 (1%), 18-25 (5%), 26-35 (27%), 36-45 (22%), 46-55 (14%), 55-65 (18%), 66 and older (13%)
Professions	K-12 Educator, Barista, Lawyer, Athletic Coach, Homemaker, Liberal Arts Student, Sales Manager, Salesman, Retired, Construction, IT Manager, Marketing, Artist, Designer, Engineer, Administrator
Past experience with electrical work	Yes (18%), No (82%)

EVALUATION RESULTS

Comfort Survey

A total of 73 participants completed the online survey. A summary of the demographics are shown in Table 1. Most of the participants actually showed some interest in having a real-time energy monitoring system installed in their home (92%). Users were willing to pay on average $42 (Min = $0, Max = $300, σ = $53) for having the transformer-based sensor installed in their breaker panel, and cost seemed to be an important factor in the adoption of this kind of technology. Based on U.S. rates, $42 would not be sufficient to cover the fees charged by most professional electricians. Interestingly, four participants already had the TED real-time energy monitoring installed system in their home. Three of the four participants reported having the device installed by an electrician and one had it installed by a friend. All four commented that they would have considered the CPCS if it were available.

Participants reported an average comfort level of 2.12 (σ = 1.31) and 4.58 (σ = 0.83) out of 5.0 for installing the transformer-based device and the CPCS, respectively. As expected, the participants reported concerns with having to open the breaker panel and being unfamiliar with electrical work. Interestingly, the average comfort level of individuals that self identified as having electrical experience in the past were only somewhat comfortable with its installation inside the breaker panel (3.08). This might be because they were more knowledgeable about the possible hazards.

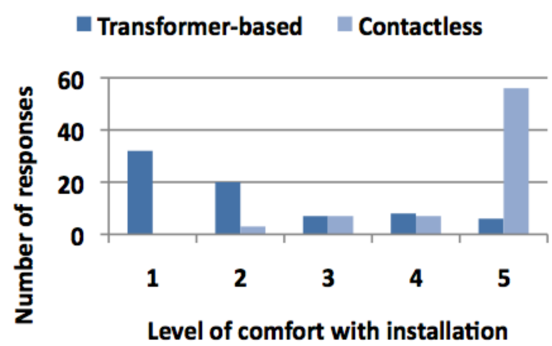

Figure 8: The distribution of responses of the comfort levels for installing each technology. (1=Not comfortable, 2=Somewhat uncomfortable, 3=Somewhat comfortable, 4=Comfortable, 5=Very comfortable)

Participants reported being much more comfortable installing the CPCS on their own (4.58) than the transformer-based device, which a Two-tailed T-Test (equal variance assumed) indicated was statistically significant ($p < .001$). Figure 8 shows the distribution of the responses for each device. Over 86% of the respondents reported being comfortable installing the CPCS (4 or higher). Some of participants that were not as comfortable (3 or less) actually cited other factors that made them reluctant to installing the device. Some cited the fact that their breaker panel was in a hard to reach area and occluded by other items or that they did not know where it was located. Overall, the results are encouraging that individuals are willing to install this kind of device themselves.

Installation Evaluation

All 8 participants in the end-user installation study were able to successfully install the power sensor in their home. Table 2 summarizes the demographic information of the participants in the study and the time it took to complete the CPCS install. Note that P1 and P2 lived together, as did P3 and P4. These participants independently completed the study without the help of their housemate.

Overall, participants took an average of 19.50 (σ = 8.12) minutes to complete the installation and verify its proper installation with at least two electrical devices in their home. Interviewed participants generally had a positive reaction to the installation procedure. One participant did require some assistance from the researcher in finding the correct placement of the sensor. In this case, the participant had two breaker panels (one main panel and a sub-panel for their new addition). Both panels were roughly the same size and it was not clear from the markings on the breakers, which one was the main, because during their renovation some of the circuits from the older part of the home were moved to other sub panel. In this case, we helped her identify the main breaker.

Table 2: Demographic information of the participants in the installation study and the time it took to install the CPCS in their home.

Partici-pant	Gender	Age	Profession	Home Style/Year	Install Time (min)
1	M	57	Manager	Single Family/ 1956	12
2	F	53	Cleaning /Services	Single Family/ 1956	22
3	M	44	Engineer	Single Family/ 1932	18
4	F	42	Homemaker	Single Family/ 1932	16
5	M	33	Construction	Apartment/ 1976	8
6	F	28	Sales	Apartment/ 1970	34
7	M	23	Student	Apartment/ 2007	20
8	M	56	Sales	Single Family/ 2003	26

When asked about their opinion on installing the calibrator in different outlets of different legs for more accuracy, the response was overwhelmingly negative. They felt at it would add too much overhead to the installation and felt the current accuracy was sufficient for what they would use it for. When asked about installing it in a 240 V outlet (such for a dryer), they generally felt more comfortable with that idea.

We did not notice any major issues with orientation. All participants understood how the device should be placed on their breaker panel. Interestingly, four of the participants did not use our heuristics on using the orientation of the breakers as guidelines on where to initially place the sensor as we had suggested in the manual. Instead, they used the sensor as a "stud finder" to locate a suitable position. After asking them about why they chose this strategy, we learned that this phenomenon was attributed to the fact that we used the analogy of a stud finder in explaining how the LED feedback worked on the device. Although this was not the intended installation procedure, this approach worked surprisingly well. When asked about this strategy, most commented that they first wanted to see where there was no signal so they could rule out those locations first. The participants had created their own understanding of the CPCS working like a metal detector or stud finder.

During the interview, participants felt the rigid body was quite constraining. They preferred the CPCS have two pieces, where each one could be attached to the surface independently. This would reduce the likelihood of accidentally shifting the placement of on the of sensor ends while trying to find the correct location of the other side. Some also found the LED feedback a bit slow. This was due to delay in the hardware trying to lock on the 60 Hz signal while some noisy inductive load was in operation.

Two participants suggested aesthetics as a potential improvement to the device. They did not want the attachment to "look out of place" and liked the ability to install the sensor on the dead panel so that the panel door could cover the installation. Some of the participants commented that the appeal of this system was the ability for them to "try it out." They would be willing to have a more permanent sensor professionally installed in their breaker in the future if they liked the system.

LIMITATIONS AND LESSONS LEARNED

A limitation to our user study was the small number of participants; however, we feel that the results are still encouraging in that most users would be able to install the CPCS on their own. We mainly focused on the installation procedure of the sensor. The next step is to have participants use the hardware for a longer period of time (as part of an energy feedback application) and study the long-term maintenance of these sensors.

We plan to conduct more performance experiments in more homes. Although our aim was to reduce the number of calibration steps performed by the user, we are still posed with an important design decision and tradeoff. In order to increase the accuracy of the system, we need to monitor both electrical legs of the home. This would either involve having the user find two electrical outlets that are served by opposite legs or install the calibrator in a 240 V outlet (if they have one). As designed, however, we feel the system offers a reasonable level of performance for most feedback applications, especially considering the performance is within the same tolerance of existing commercial products. Based on the feedback from participants, they prefer the easier-to-deploy approach over gaining performance.

As predicted by Beckmann *et al.* and others, aesthetics was an important consideration cited by two individuals despite the sensor being installed in the garage and utility closet. Also, as with most interfaces, immediate feedback is critical. Although we tried hard to design the hardware to allow the LEDs to respond quickly, the users still felt there was noticeable lag in its response. However, the LED feedback was still critical in helping users place the sensor. Prior work in this space has suggested that users often struggle with sensors that require proper orientation.

Orientation was an inherent part of the technology that we had to design for early. It took a combination of building the hardware to support real-time placement feedback and soliciting feedback from users on how to show that information on the sensor. In this case, simple LEDs were all that was required.

There is definitely value in partial installations. For example, if the user could only pick up one of the electrical feeds, the sensors still provided consumption data for some of the appliances. This helps relieve some frustration that might have developed if nothing worked. The use of the stud finder analogy proved important in allowing the users to associate a familiar metaphor to the system. The participants had very little knowledge of how exactly the sensor worked, but they did eventually understand that we were trying to remotely pick up the power behind the panel.

CONCLUSION

We presented some encouraging results for a new whole house, power consumption sensing system capable of gathering real-time power use that does not require installing a current transformer around the electrical feeds in a home. Our system offers contactless operation by simply placing it on the outside breaker panel in a home. User evaluations indicate that participants generally had a positive opinion about the installation procedure. All 8 participants were able to successfully install the CPCS in their homes. In addition, our online survey showed that over 86% of the respondents would be comfortable installing the CPCS on their own.

We hope this technology will enable HCI and Ubicomp researchers deploy energy monitoring applications faster and more easily without having the overhead of installing the sensors in the breaker panel and consulting a professional. Although we only focus on the 60 Hz power consumption in this paper, it is important to remember that our sensor is broadband (up to 1 MHz) and has the ability to do some load identification based on higher frequency harmonics, similar to the techniques in [10]. In addition, by combining the CPCS with Patel *et al.*'s plug-in powerline event detection system [13], we now have the tools to detect an individual electrical event and its associated current consumption in an easy-to-deploy manner. The combination of these technologies now provides the appliance-level disambiguation the community has wanted.

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