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Outlet Power Monitoring Using Wireless Sensor Networks

Capstone Project Paper

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Abstract

The need for increased power monitoring in residential and commercial units is becoming increasingly self-evident by the ongoing shortage of natural resources and rising costs of electricity. This need has been supported by recent government and private policies towards reducing power consumption and better power monitoring. Several startups and organizations have developed strategies to improve power monitoring; this paper will provide an overview for the shortcomings of such attempts such as: cost, ease of integration (as well as being non-invasive), and functionality. Our system is one that implements these features by taking advantage of several new technologies, including energy harvesting techniques and innovative low-power wireless protocols and hardware. A brief discussion of these new technologies and how they provide improvements to current power monitoring solutions will be made. The focus of this paper will be on the analog front-end interface to the power monitoring sensors in the system. For building a non-invasive power monitoring solution, two current-sensing technologies are implemented: inductive sensing using an air-core inductor, and sensing using an energy harvesting transformer. Each solution for current-sensing provides a challenge for filtering, amplification, buffering, and ensuring that the sensor is sensitive enough to changes in current draws.

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Introduction

The consumption of the world's natural resources has been increasing at an alarming rate for many years, and studies have shown that the earth's natural resources will soon be depleted in the next couple of decades, if we continue to consume energy at the current rate. A plethora of research has been conducted to find new ways to generate power from the earth's resources and to discover new renewable energy sources. A global push for this research has spawned entire industries dedicated for this purpose. Although great strides have been made from this research, it is imperative that we reduce our power consumption as a human population, if we hope to continue using the technologies that are so prevalent today, and that we have come to consider as necessities. The industry is constantly pushing to produce lower-power consumption electronics, but with the proliferation of electronics in the average end consumer's life, it will become imperative that consumers monitor their power consumption.

From an end consumer standpoint, electrical energy composes a large portion of our energy consumption. Other sectors such as gasoline and natural gas also compose large sectors, but our consumption of electrical energy comes in so many forms that detailed monitoring can prove to be very useful. Energy in other forms, e.g. gasoline, tends to be consumed in specific ways that are already easily monitored, e.g. for gasoline, it is easy to find out how much gasoline a consumer uses for transportation purposes. Electrical energy is consumed in a myriad of different ways, at home and at work, so as consumers, we could greatly benefit from specific, detailed monitoring of the ways in which we use electricity. By knowing exactly how electricity is being consumed, consumers are put it a much better position to reduce their electricity consumption. Over 40 studies conducted between 1975 and 2000 have shown that having meter information in a central, visible location reduces energy use by between 10-14% on average [1]. In addition, as building design becomes more efficient, plug-load electricity consumes a larger proportion of the overall energy usage, accounting for 45% of power consumed in buildings that have reduced their HVAC and lighting loads [2]. While reducing our carbon footprint is nice, the driving motivation for reducing electricity consumption is monetary savings, at least from a consumer standpoint. With the rising cost and demand for electricity, this motivation will only continue to grow stronger.

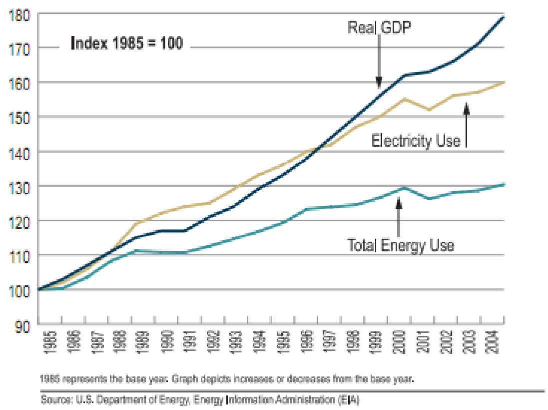


Figure 1: Graph of GDP and energy use in the United States over time

To obtain this set of detailed, specific information about electricity consumption, we have devised a wireless sensor network that monitors plug-load activity. This network will be able to monitor power usage at individual outlets, aggregate the data, and report useful information about electricity use to the consumer. The user will be able to access power monitoring data from a smartphone or traditional browser, including how much power each outlet in the unit is consuming independently. This is made possible by our topology, a mesh network of sensors that is able to report specific power monitoring data for each outlet, but also aggregate data for the entire unit. This mesh network will be able to interface directly to a hub that routes data to a web server, which enables accessing this data from smartphones and browsers easy (see Figure 2 for web interface).

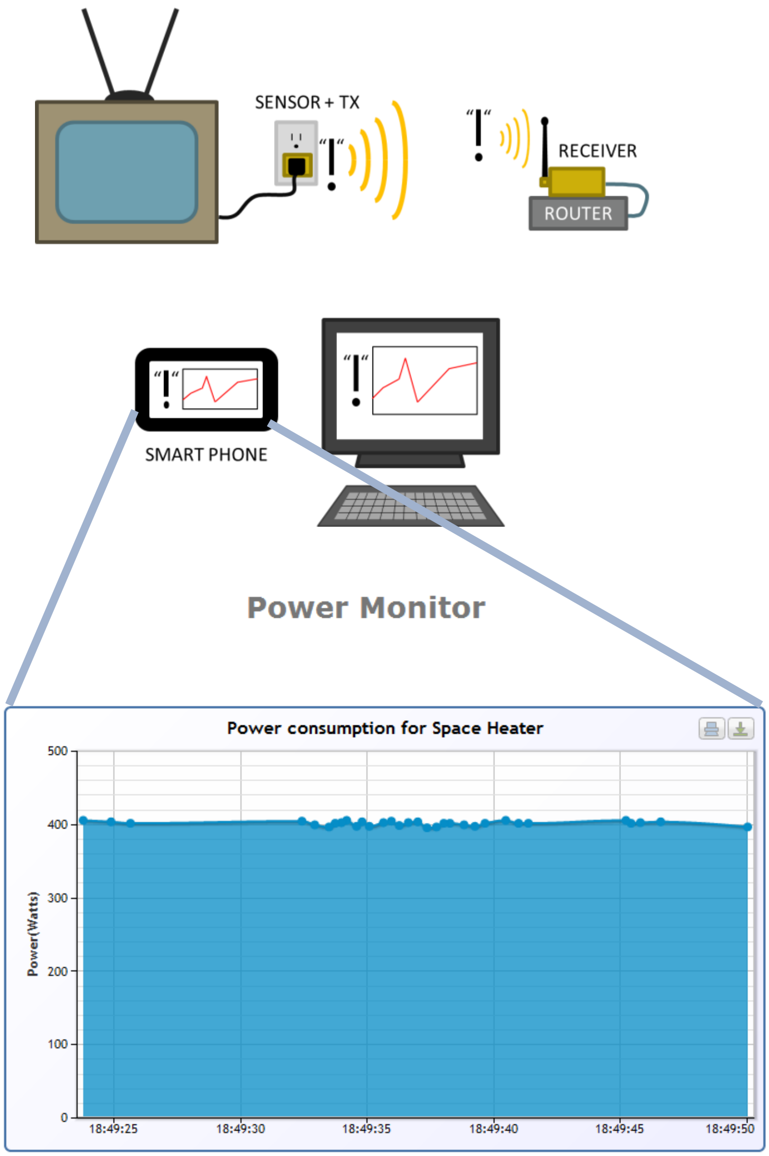


Figure 2: Overview of power monitoring system and the power monitoring web interface. This interface is available through a URL that can be accessed from any web-enabled device.

Literature Review

Power monitoring solutions for residential and commercial units have existed for a long time, and here we will examine the shortcomings and pitfalls of such solutions, and how we improve upon them in our project. We will also examine research done in the field of energy harvesting, specifically harvesting off of power supplies without direct contact with the conductor. This research played a big role in enabling us to improve upon the existing power monitoring solutions on the market today.

P3 International

One major company with power monitoring solutions is P3 International, who is well-known for their home power-monitoring product: the Kill-a-Watt, pictured left. To use a Kill-a-Watt, the consumer connects the device between the appliance and the outlet. The voltage, current, power, and frequency data corresponding to electrical usage are then displayed on the LCD screen. The product is intended for users who wish to understand electricity consumption of specific appliances, rather than obtain a holistic picture of their building's power usage. This device has no wireless capabilities, so easily monitoring multiple devices in your unit is not possible. The device is also large and bulky; having one of these for every device in the household would be an aesthetic and intrusive nightmare. At $20/outlet, the price is decent, but still not scalable for monitoring a multitude of devices throughout the unit.

EnergyHub

EnergyHub is a start-up complete with high quality marketing and a well-refined product. Their products are plug-through like the Kill-a-watt and data is sent wirelessly to a central hub which is also a user-friendly touch-screen display. Data can also be displayed on a web or mobile apps. There are a couple of downsides to their product. First and foremost is the cost, which comes out to about $40/outlet ($300 for the whole system); this is cost-prohibitive for the vast majority of power-conscious customers. Another very important factor is that they are using Zigbee, an inefficient wireless network protocol compared to 6lowpan (IPv6 over Low power Wireless Personal Area Networks), the wireless network protocol that we will be using. For the application of power monitoring, 6lowpan has lower power consumption and is better suited for communication with normal internet-enabled devices such as laptops and smartphones. 6lowpan uses IPv6 as a protocol for sending data, which is used by almost every internet-enabled device on the planet, while Zigbee uses a special protocol only designed for communication within the individual nodes of the network (in this case, the socket devices). Another factor is that their plug-through outlets cover two sockets and only give you one (see Figure 3), which is undesirable. Like the Kill-a-watt, the socket monitors are bulky and block other outlets. The vision of having device-specific monitoring for the whole house does not scale well with these types of devices.

Figure 3: EnergyHub power monitoring socket, only providing one outlet but blocking both outlets on the wall

There are other companies like EnergyHub (Powerzoa, Talkingplug) that follow along the same lines of having outlet specific monitoring, a wireless network of nodes, and smartphone/browser interfaces for monitoring power consumption, but they are not unique in their solutions, and have the much of the same pitfalls as EnergyHub's solution.

Energy Harvesting

In addition to the shortcomings mentioned before, there is one large factor that will be differentiating our product from the existing solutions: how we power our device. The examples mentioned before all use direct contact methods to power their devices; i.e. the devices that are installed on the outlet make direct contact like any other appliance in your home. Because of this, the power monitoring device must deal directly with a 120VAC, 60 Hz signal to power a small LCD screen or a simple RF wireless module. The components on the device do not need that high of a voltage of course, so additional circuitry is needed to step down that voltage to a reasonable value (3-5V DC usually). Adding this circuitry adds significantly to the cost, size, and power consumption of the device. This is evident from looking at the cost and size of the previous devices mentioned. Power consumption figures for commercially available devices are not available, but given the constraints of their design in terms of wireless protocol selection and power supply method, it cannot be less than 100 mW, which our device improves significantly upon. Using 6lopan as a wireless protocol and energy efficient duty cycling and hardware for wireless communication, our system uses 100 uW of quiescent power.

Our device takes a different approach for supplying power, and that is a non-contact method called inductive coupling. This is a very well researched method that has produced many papers [3]. With this method, there is zero current draw from direct contact with the supply from the wall. Instead, a transformer is built around the prongs using a magnetic core with coils wrapped around it. By Faraday's law, a current is induced in the coils which can then be used to power our device. This is a much safer method since there is no direct contact with the 120VAC signal, and also needs less circuitry since we are dealing with a manageable voltage and current. This is especially useful for applications where interruption of the power circuit for the device can't be done, e.g. network servers, cooling units, and other industrial applications where this non-invasive, easy-to-integrate device would be the best option. [3] reviews the physics behind transformers, and how a current and voltage are induced in a secondary transformer in response to a 60 Hz power signal. An added benefit of using a transformer is that the transformer signal can also be used to monitor the current being consumed by the device, since the transformer voltage signal is proportional to the current being drawn.

Methodology

In this section, we will outline the experiments conducted to design and verify the analog front-end for our sensors. The purpose of the sensing circuitry is to filter, amplify, and provide a buffer for the signal coming from our current sensors. As mentioned previously, we will look into sensing options for two power monitoring configurations: no-contact energy harvesting using a transformer, and direct-contact to power prongs. We will investigate the direct-contact method first.

Direct-contact Sensing Methods

After speaking with experts in the field and considering options used by other power monitoring devices, we came up with two potential current sensors: a one-axis Hall Effect sensor, and a simple inductor with a high inductance value (68 mH). Both sensors work in the same way: a current in the AC prong generates a varying magnetic field around itself, which in turn generates a current in the current sensor. We will derive the sensitivity and noise floors of both sensors -- two of the most important figures when considering which current sensor to use. The voltage induced in the inductor is given by [3]. The equation is reproduced below for convenience:

$$V = N\mu_0\mu_r w f I \ln\left(1+\frac{h}{r}\right)$$

where V is the voltage induced in the inductor, N is the number of coils, u_0 is the permeability of free space, u_r is the permeability of the magnetic core, w is the width of the inductor, f is the frequency of the AC current, I is the RMS vaule of the current in Amps, h is the height of the inductor, and r is the distance of the inductor from the AC line. These values were approximated based on the Murata 13R686C datasheet, and the values we used to approximate the voltage is as follows: N = 360, $u_0 = 1.257 \times 10^{-6}$, $u_r = 1$ (air-core), w = 50 mm, f = 60Hz, I=1A, h= 50 mm, r=25 mm. With the following figures, we obtain a calculated sensitivity of 1.5mV/A. The theoretical noise level of the inductor will come from the thermal noise of the parasitic resistance associated with the inductor. This particular inductor has a resistance of 150 ohms, so the rms noise is given by: $\sqrt{4k_BTR\Delta f} = 12.2nV$. In practice, when testing the sensor with an oscilloscope, the observed noise was higher, at about 0.1mV when far from any current-carrying wire. This noise could be from other ambient sources of noise and RF signals.

	Inductor	Hall-effect sensor
Cost	$0.36	$3
Power	Passive element	11mA @ 5V
Sensitivity	1.5mV/A	14mV/A
Noise (rms)	12.2nV	3.5mV
Area	See below	See below

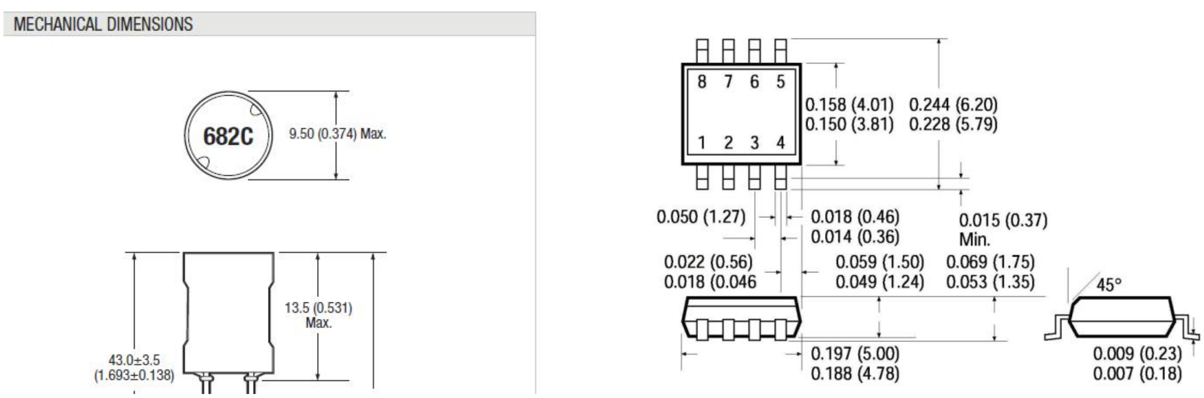


Figure 4: Comparison of a hall-effect sensor and an inductor for sensing current

Figure 4 gives a summary for the comparison of the two sensors, as well as a comparison of the dimensions. The figures for the hall-effect sensor were taken directly from the GMW CSA-1VG hall-effect sensor datasheet. The greatest advantage the inductor had over the hall-effect sensor was the fact that it was a passive sensor, i.e. it does not draw power to perform the sensing. It is also cheaper and has a lower noise floor. Smaller inductors might work as long the sensitivity does not fall below the noise level. They will need more amplification since the signals will be weaker, i.e. lower inductance and fewer coil turns.

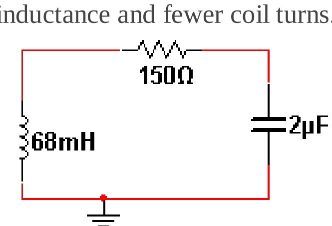


Figure 5: Setup for current sensor with a capacitive filter. Resistor shown is the parasitic resistance of the inductor. Current is induced in the inductor by a perpendicular magnetic field from the primary prong

Figure 5 shows the setup for testing with the inductor. We have also tied a capacitor to the inductor to act as a low-pass filter and filter out some of the very high-frequency noise. Since we are only interested in the 60Hz signal, we attempt to filter out any signals above 60 Hz, without significant attenuation to the actual 60 Hz signal. An appropriate capacitance of 2uF is chosen. Since the inductor and capacitor values dominate the small resistor's effect, this circuit behaves like an LC tank with a cutoff frequency of:

$$f_T = \frac{1}{2\pi\sqrt{(68m)(2\mu)}} = 431.569\ Hz$$

which filters out the high frequency noise but does not significantly attenuate the 60 Hz signal. Instead of placing the 60 Hz signal in the pass-band of this LC filter, we could attempt to place the 60 Hz signal at the resonant peak of the filter. By choosing an appropriate capacitor of 100 uF instead of 2uF, the 60 Hz signal would be placed at the peak and all lower and higher frequencies would be attenuated with respect to 60 Hz. The peaking of the resonant frequency will be dependent on the Q of the inductor. With higher Q factors comes high peaking. Active filtering strategies are also possible to give sharper roll-off, but they would consume more power and require more area to implement. For our application, sharp-roll off and higher order filters are not needed. We only wish to filter out some of the high-frequency noise.

We now have a filtered signal at the output of the capacitor. We would like to amplify and bias this signal so that the ADC on our microcontroller can read the AC voltage in the 0-3V range. We could use a simple non-inverting amplifier using one op-amp for this task, and indeed, this was our first attempt, which worked well. However, the power supply for our circuitry only generates positive and ground voltages, and our circuit uses a negative supply voltage for the op-amp. To get around this, we generate an intermediate voltage of 1.5V to act as a new ground voltage. This way, 3V can be the positive supply, ground (0 V) will be the negative supply, and 1.5 V will be the new ground for the amplifying circuit. This serves to also bias the AC signal at VDD/2, so that the voltage beings relayed to the ADC never drops below ground.

To generate this 1.5V reference, we use a voltage divider circuit with two resistors to split the 3V in half. To ensure that the circuit that uses this reference voltage does not distort it, we use a voltage follower as a buffer to supply this voltage. See Figure 6 for a detailed schematic of the circuit. The output of this circuit is then fed directly to the ADC where it is sampled, filtered further in the digital domain, and the current is calculated.

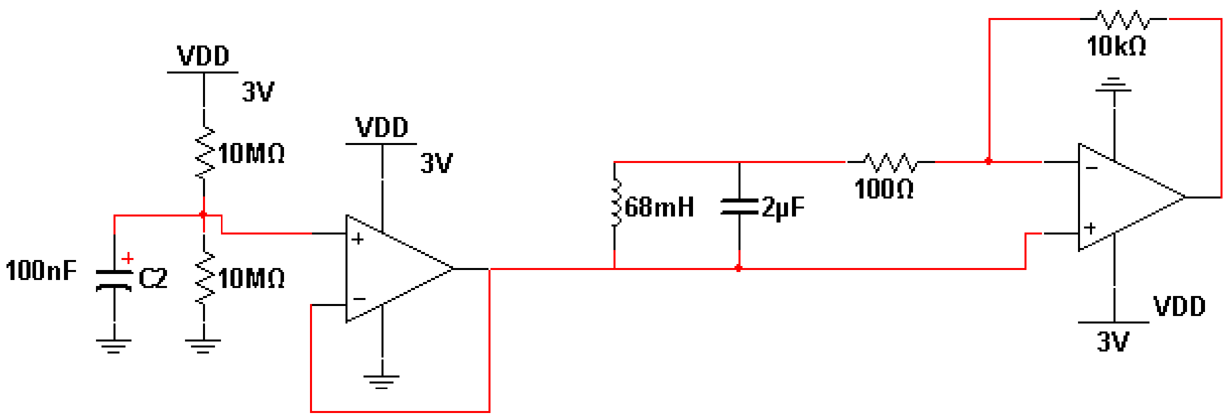
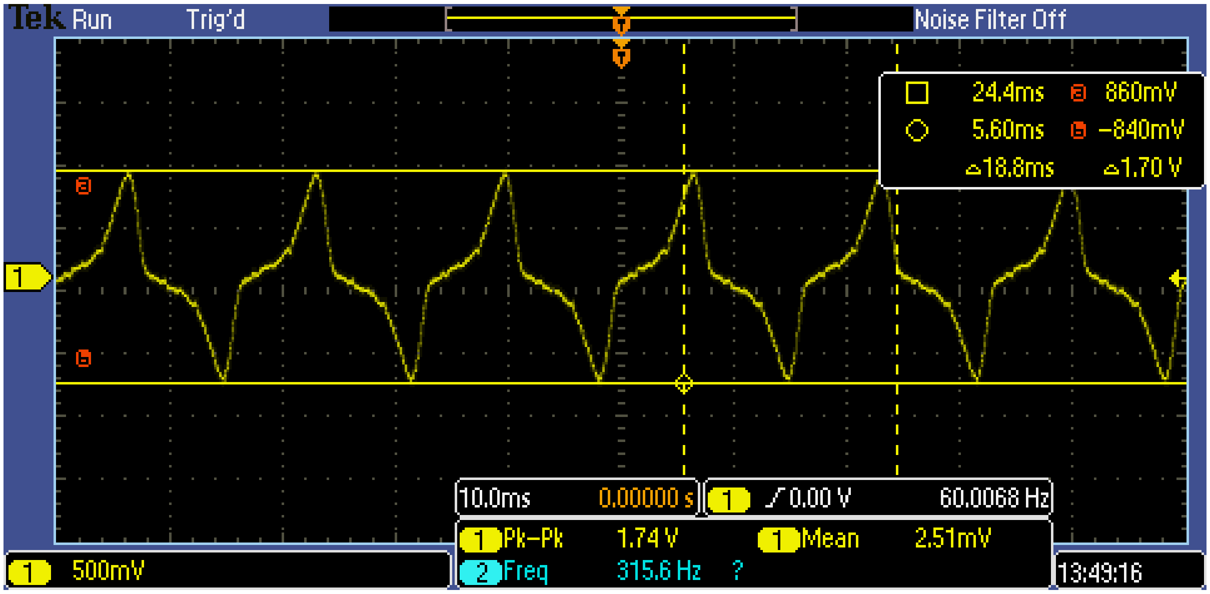


Figure 6: Filtering and amplifying circuit combined. The amplifying circuit runs off of a 3V VDD supply from the AC-DC conversion circuit. Since op-amps need a positive and negative rail supplies, 3V is used as the positive rail, ground as the negative rail, and 1.5V is used as the new reference. The 1.5V is generated using a voltage divider + voltage follower op-amp circuit (left-side of the image). 100 nF capacitor is used to filter noise on the power supply line. The op-amp amplifying circuit (right op-amp) is just a simple non-inverting amplifier, with gain 10k/100 + 1 = 101.

Non-contact Sensing Methods

For the non-contact method of power monitoring, we readily have available the transformer which produces a signal which is proportional to the current draw of the device, so no additional sensing hardware is needed. This signal is not sinusoidal but its peak-to-peak voltage varies linearly with current draw. See Figure 7 for the waveform of the transformer output and a picture of the transformer. Sampling this signal in the ADC and calculating the RMS value, as is done with the inductor, produces a signal that is linear enough to reconstruct the current draw in the processor code.



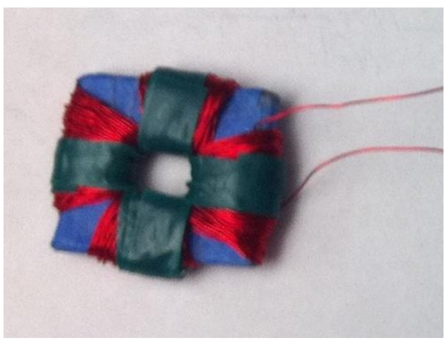


Figure 7: (Top) Transformer secondary with mu metal magnetic core and 500 windings. (Bottom) Non-sinusoidal transformer voltage output at 60Hz. Notice how the signal is pristine without much noise, so filtering is not necessary for this circuitry

Unlike the inductor sensing circuit, we are not only using the transformer to sense the current but also to power the wireless radio and biaser/buffer. Hence, we make sure to draw the absolute minimum amount of current from the transformer in the sensing circuitry, aiming to provide a very high impedance interface between the transformer and the ADC. This is accomplished by a buffer/biaser topology. No amplification is needed since the sensitivity of the transformer is already high enough (400mV/A) to be in the suitable range for the ADC.

To build this buffer/biaser, we built an inverting amplifier with a gain of 1, and fed a DC signal equal the positive input to bias the AC signal (see Figure 8 for circuit diagram). The equation for the output of the circuit is:

$$V_O = -GV_i + (1 + G)V_b$$

Where V_b is the bias voltage fed to the positive terminal of the op-amp and G is the gain (1). See [4] for a derivation for the output of the circuit. With a gain of 1, this bias is doubled at the output, so we select our voltage divider resistors appropriately to halve the bias voltage at the positive terminal. We choose large resistors at the transformer input signal to minimize current being drawn from the transformers; we

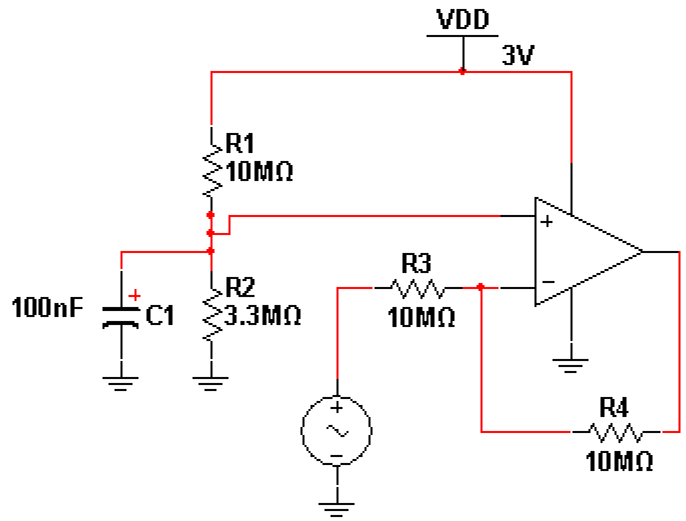


Figure 8: Buffer/Biaser for transformer signal. Voltage divider on the left side of the image is used to add a DC bias to the signal, and C1 is used to filter noise on the power supply line. The AC is buffered with a gain of 1, and large resistors are used to provide high input impedance. The output of the op-amp is fed to the ADC in the microcontroller.

chose the biggest resistors available in our lab, 10M ohms, to provide an effective input impedance of 20M ohms, which reduces the current drawn from the transformer to 3V/20M = 150 nA, a negligible amount of current draw.

Results

In this section, we will discuss the results of actually fabricating the hardware and testing it out with real devices. Two devices were fabricated: a non-contact transformer that interfaced to a circuit card, and a printed circuit board with three slits for prongs and all circuitry soldered on. Performance of the sensing circuitry will be discussed in terms of sensitivity, noise, and power consumption.

Direct-contact Sensing

Shown below is the full circuit for direct-contact power monitoring, including the AC-DC conversion circuitry, wireless module and microcontroller, and the sensing circuit labeled in red. The inductor is the biggest piece of hardware on this board, and dominates a good part of footprint. The part number is Murata 22R686C. Using a large inductor was necessary to get a good signal response from the nearby current-carrying wire. In addition to having a high inductance of 68 mH, this inductor has thick wires which reduced the parasitic resistance. The parasitic resistance of the inductor is 150 ohms, significantly less than other inductors whose resistances usually fall in the 500 ohm range. The circular geometry of the inductor also gives it an advantage over its surface mount

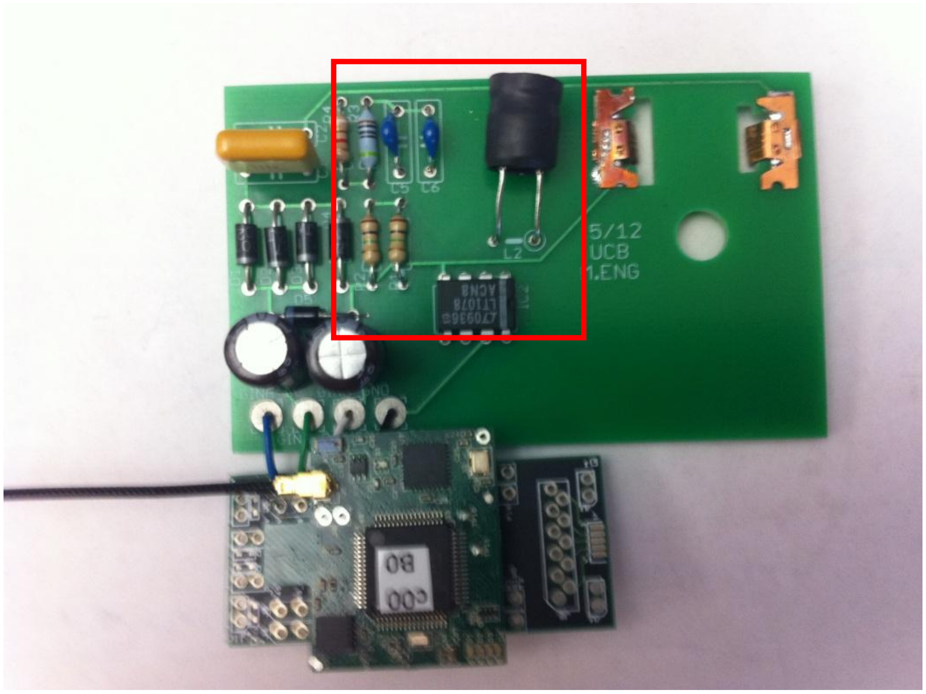


Figure 9: Full direct-contact power monitoring circuitry, with sensing circuit labeled in red

counterparts, since it enables it to be bent into the correct orientation relative to the magnetic field. This is crucial to getting a good signal response.

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The op-amp chosen is LT1078ACN8. For low-power applications, this is a good choice of op-amps. The op-amp can operate under voltage supplies as low as 2.2V and as high as 22V. It only consumes 40 uA of current while providing a maximum gain-bandwidth product of 200kHz [5], more than enough for our application (100*60 = 6kHz). In addition to this, the chip provides two op-amps in one package, which is perfect for our application. The circuit was able to interface to the AC-DC conversion circuit without any undue load because of the choice of the low-power op-amp and high value resistors for the voltage divider. However, the 3V reference from the GINA was used instead of VDD from the AC-DC conversion circuit for the AC bias reference since it provided a more stable output (the GINA 3V reference comes from a voltage reference on-board).

The sensitivity of the circuit to the nearby current-carrying prong is depicted in Figure 10. The inherent sensitivity of the inductor was found to be around 1mV/A, and the noise floor was seen at about 100 mA, which corresponded to a 0.1mV output from the inductor.

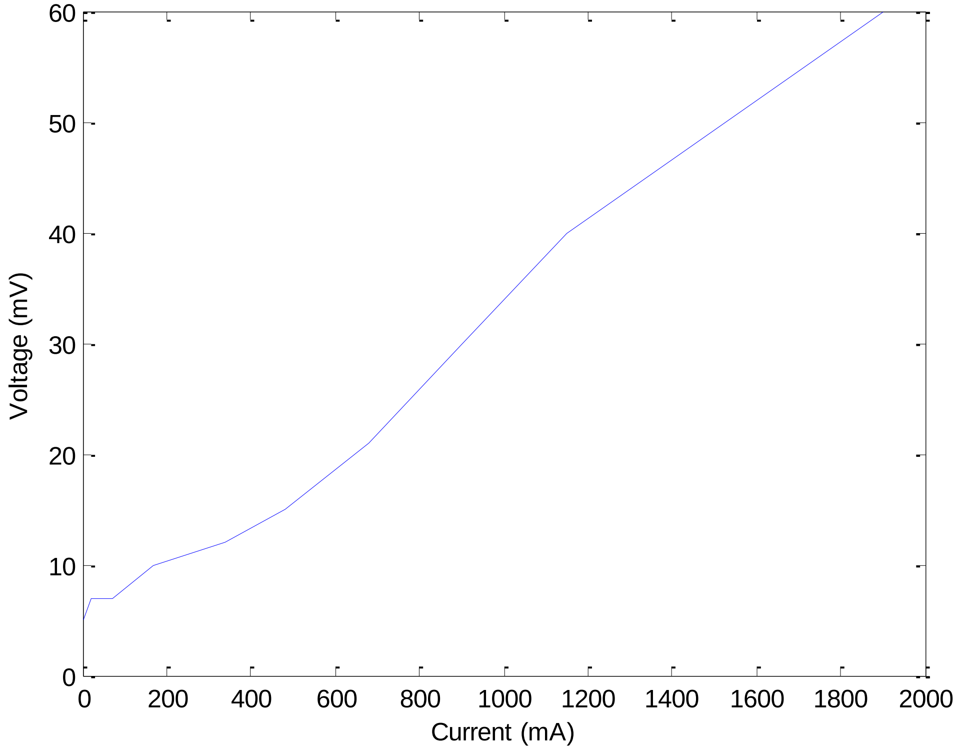

Figure 10: Sensitivity of the current-sensing inductor after being fed through the amplifier with a gain of 35. The noise floor of the sensor is seen around 100 mA. This experiment was conducted while measuring current draw of a light bulb, whose current draw was being controlled by a Variac transformer

Non-contact Sensing

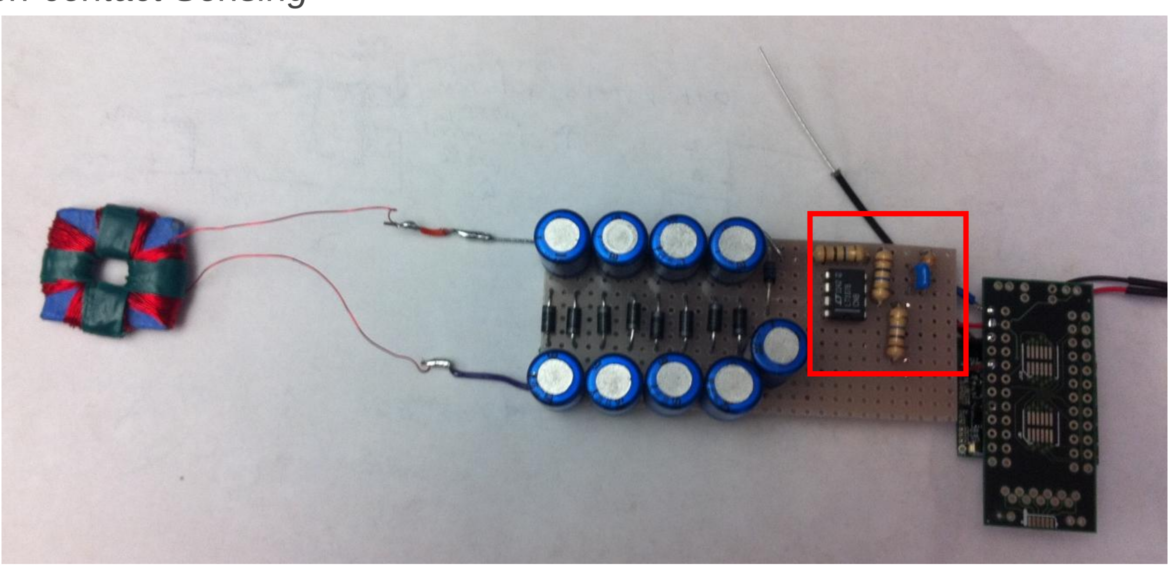

Figure 11: Full circuit board for the no-contact power monitor. Sensing circuit is labeled in red.

Shown above is the full circuit for no-contact power monitoring, including CW multiplier circuit, wireless module and microcontroller, and the sensing circuit labeled in red. The CW multiplier is needed to step up the voltage from the harvesting transformer to above 3.3 so that the GINA can be powered. The sensing circuit on this board is much smaller than the direct-contact method, because there is no need for a sensing inductor or chip. The signal from the transformer is routed directly underneath the board.

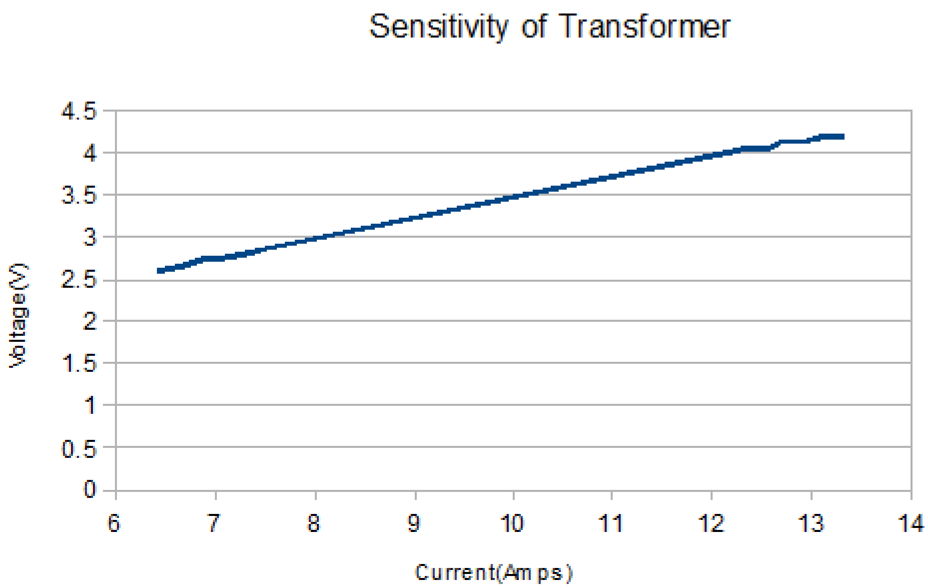

Figure 12: Voltage response of transformer to current flowing through prongs of the plug. This test was performed using a heater with high and low settings, consuming in the range of 6-12 Amps.

The same op-amp is chosen for the previously mentioned advantages. Because this transformer has a high quality magnetic core that concentrates the magnetic flux, its sensitivity to the current-carrying wire is much higher. Our measurements indicated a 400 mVpp/A sensitivity (see Figure 12). A challenge of using the non-contact method we developed was that it could only harvest energy from devices that drew a lot of current, at least 12 amps. This is the reason we present the sensitivity tests for such high current draws. With further optimization and development of better harvesters, the non-contact method should work for devices that draw less current.

Conclusion

We have demonstrated two form factor solutions to the problem of non-invasive, easy-to-integrate, and functionally-rich power monitoring. The biggest advantage it has is its small size and thickness compared to other solutions currently on the market, which makes it a very non-invasive solution. In addition to its small size, its innovative wireless module and protocol that speaks IPv6 allows for easy integration into any network that talks IP, eliminating the need for a screen on every node and facilitating aggregation of data to a server. With custom fabrication of an integrated circuit that incorporates all the hardware on our solution, the size can surely be reduced to become the size of a single circular outlet, becoming almost invisible to the user when sandwiched in between the wall and the plug. This small size and thickness coupled with the low cost of production for such a device would surely enable this product to be successful as a mass produced sensor that could be installed easily on every outlet.

There do remain challenges in sizing down such a device, however. Namely, the power supply for the direct-contact method remains a challenge in terms of scaling down. For the non-contact method, the transformer needs to retain its size to enable its energy harvesting capabilities. Also, we have also not investigated measuring of voltage in the power lines, which is necessary for measuring power factor and getting a better idea of the nature of the power consumption of the device, whether it be reactive or real power consumption.

These challenges present a good opportunity for further research, and with more time and effort, there is a good reason for hope that such a project will succeed.

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