

Non-Contact Wireless Power Monitoring

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Technical Report No. UCB/EECS-2012-131

<http://www.eecs.berkeley.edu/Pubs/TechRpts/2012/EECS-2012-131.html>

May 30, 2012

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Abstract

The most recent and reliable data show that building occupants are spending increasing amounts of money on electric power, a significant portion of which is used to run plug-load appliances. However, there is good evidence to suggest that with accurate, complete, easy-to-digest information on how, when, and where power is being used, consumers can then respond by reducing wasted energy through change in usage patterns, thereby reducing personal costs and, indirectly, problematic greenhouse gas emissions. Therefore, we have proposed and designed a system of small, plug-through network nodes that monitor power usage on individual plug-in devices and integrate that information into an easily comprehensible web format. In order to build a small, safe, cost-effective product, we designed a circuit that inductively harvests electrical energy from the power flowing through the plug prongs when the device is turned on. That signal is rectified into a DC component that charges a capacitor to power the whole network node, while the AC ripple is converted by a sensor mote into a digital communication packet that signifies the amount of power (along with other relevant data) being consumed in a given window of time.

Introduction

Due to the well-known personal (monetary) and global (environmental) costs associated with today's current and growing use of fossil fuel energy, societies around the world, led by scientists and engineers, are beginning to take steps to reduce the world's reliance on energy produced from fossil fuels. One side of the efforts, perhaps the one given more coverage in public media, is concerned with the supply of energy, and how fossil fuels may be replaced with cleaner, sustainable sources of power.

A major and persistent criticism of the aforementioned approach is that alternative energy technologies are too slow in coming and too uncertain in their promise to match the magnitude of the problems such as those caused by the increase in energy demands by the developing world, leading to higher energy prices, and those caused by global warming, which include the destruction of fragile and valuable ecosystems. According to this school of thought, the plan of attack with respect to the energy crisis should regard the prevalence of fossil fuels as in some sense inevitable, at least in the near future, and should focus instead on encouraging consumers to reduce overall energy usage, thus conserving the fossil fuel sources.

There are two significant problems with this thinking. First, engineers can only go so far in designing products for energy efficiency without either hitting physical and technological limits or sacrificing commercially valued attributes of products like performance and cost. Secondly, consumers may only be so willing to curb consumption of energy before making unacceptable changes to their own lifestyles. It follows from these facts that consumers are likely to only conserve energy where it is being used in ways not conducive to their needs and wants, or, in other words, wasted.

Unfortunately, even well-educated consumers are often unaware of where and how much energy is used across the many electronic devices in their homes and offices. As it

happens, a significant quantity of electricity is wasted by appliances plugged into electrical outlets. If consumers were aware of how specific plug-in devices contributed to their energy bills, they would likely adjust behavior to cut out wasted power usage. Indeed, there is evidence to suggest that consumers would be willing to more carefully adjust electrical power consumption if provided the relevant information.

In order to provide consumers with the information necessary to reduce energy wastage from plug-in electrical devices, we have devised low-cost miniature plug-through circuits that can inductively sense and harvest the power flowing through a given plug-in appliance and wirelessly broadcast the power usage data into a network via radio. The network uses a central hub to aggregate the incoming data, which is then converted via software into a user-friendly interface that displays power usage patterns to the user on demand. A helpful pictorial diagram below (left, Fig.1) depicts the overall operation of our creation: an example load, in this case a television, is drawing current, whose magnitude in time is read by our plug-through harvester/sensor (whose electromagnetic scavenging from the current through the prong is shown in the image on the right, Fig.2). This data is then broadcast to some sort of router, where it is then passed on toward a website or application that displays the information as a power flow in an intelligible graphical user interface.

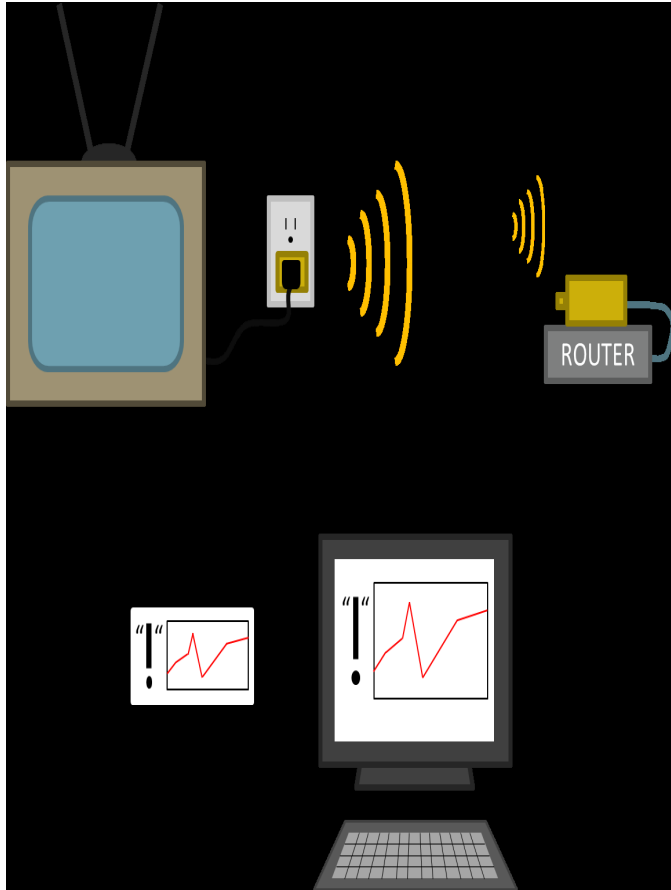


Figure 1: General System Diagram

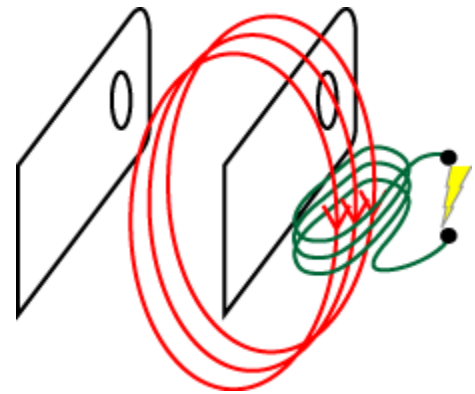


Figure 2: Inductive Harvesting from Prong

This paper will start by introducing cursory evidence that justifies the need for the product we have invented. Next, we will discuss the current work being done in the space of plug-in power monitoring, including the advantages, shortfalls, and relevant design considerations of existing products in the market. The following section will explain our technical approach to improving the plug-through power monitor, with special focus on the circuit used to generate a steady DC power supply to the amplifying, processing, and broadcasting circuitry. After that, this paper will document the results of our work. Finally, we will conclude with a summary and suggest what implications our findings may have.

Literature Review

Necessity

To begin, our project requires motivation in the form of a need that it fulfills. The need that we intend to fulfill with our innovation here is that of conserving the use of electricity. This need arises because an increasing volume of consumer income is being spent on purchasing electricity, as demonstrated by the facts that

A) Aggregate electricity use is on the rise, and has been for quite some time (Fig. 3).

B) Per kWh dollar expenditures is also increasing across sectors in this country (Fig. 4).

Some representative data by the Missouri Department of Natural Resources is shown below[1]

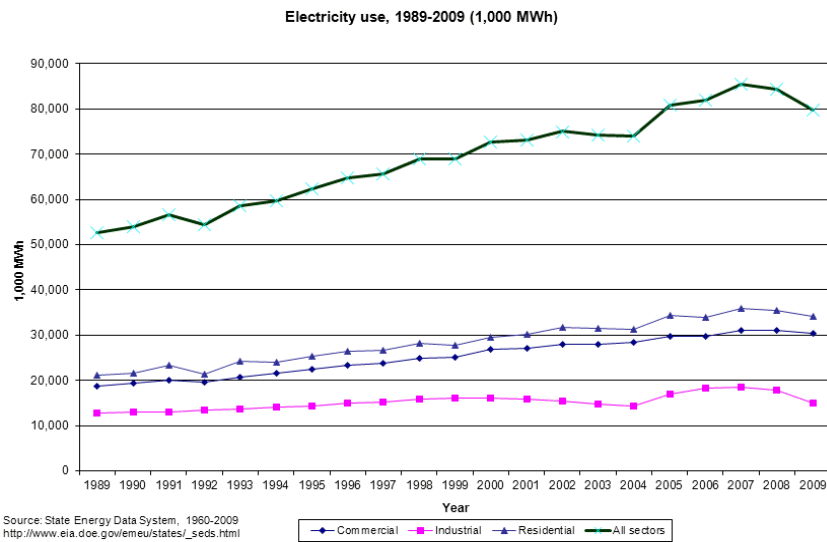


Figure 3: Increase in aggregate electricity consumption with respect to time.

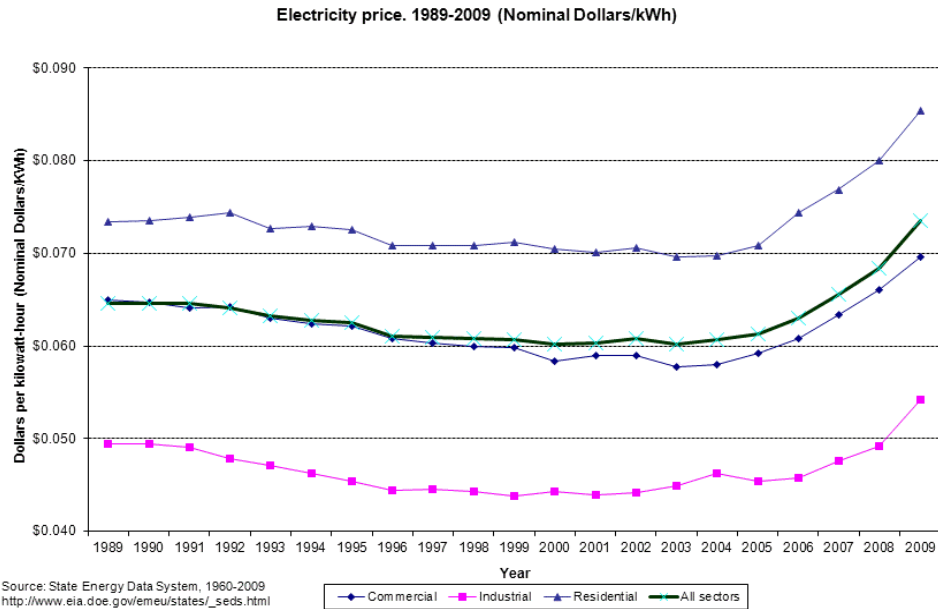


Figure 4: Rise in electricity prices across the board over last several years

But of course, there is need of evidence to defend the claim that the a significant portion extra energy being consumed is actually being wasted. In fact, the environmentalist group Sierra Club, specifically the Virginia Chapter, argues [2] that up to 10% of the power draw of the “average household” comes from “vampire” current, which is power pulled from the mains by plug-load devices even while they are switched off, which is by definition when they are not in use. This obviously does not include instances where people negligently leave on devices that they are not using. The Sierra Club even advocates the use of power monitoring devices such as the “Kill-a-Watt” in order to determine the absence or presence of “vampire” loading, a role that we might hope to usurp with our own invention under discussion here. Furthermore, they encourage practices such as unplugging certain appliances when not in use, which the user may not think to do unless convinced that significant wastage is occurring.

Thus, the final argument needed to defend the commencement of our undertaking would be that electricity users, once given access to information about how energy is used or wasted

in their households, will move to make significant conservation decisions. Fortunately, this claim has empirical support. A recent study by the U.S. Department of Energy showed [3] that 71% of consumers reduced energy consumption upon viewing visual representation of their actual power consumption. Moreover, a pilot program by IBM demonstrated [4] that the steps taken by such informed customers amounted to approximately 11% in energy savings. It is clear, then, that a user-friendly product giving accurate, reliable electricity consumption data has the potential to motivate customers to use less electrical power. A product that can deliver this service affordably and effectively, then, has great potential for success.

Prior Solutions

The goal for our project is the development of a network-enabled low-cost, low-power energy monitor for plug-in electrical appliances. This space has received a great deal of interest in the past decade. For instance, one well-known commercial product for providing power-monitoring data on display is the Kill-a-Watt[5], pictured in Appendix C. This product, while widely sold, shows quantities like voltage, current, and power on an LCD display on the body of the product itself, providing information only locally rather than remotely. This feature expands the product's dimensions such that the space of two sockets is taken merely to measure consumed at one of the pair! This is certainly a design flaw upon which we intend to improve.

At the large scale, the Smart Grid technology has often been cited as a public-sector solution whereby power flow to a building is dynamically managed based on user pricing specifications, such that some fraction of otherwise accessible power is in practice unavailable at times of high load demand for users who opt into the program[8]. Over the Smart Grid, however, we intend to emphasize the fact that we do not handle cutting off and restoring power, preferring the user's discretion in plugging and unplugging to our own. Furthermore, while utilities have been interested in providing sub-metering technology to users, which would enable

them to more finely monitor where power is coming from, we offer that technology directly through our product with the network capability to also aggregate the information to provide overall power consumption data.

A product that more closely resembles our own with respect to function is the EnergyHub Monitor[10]. This product feeds information from individual plug monitors to a central display that shows the user how and where power is being used in the household or building. Of course, there display is a custom product, but while they are working on technology friendly to existing operating systems for computers and smartphones, we made this a feature of our very prototype.

On the energy harvesting side, some work has been done to measure power through a plug, except the measurement was taken around the cable rather than the prong of the plug. Bhuiyan et. al. (2010) demonstrated[7] that an inductive transformer made of wires and mu-metals could be shaped and fitted around a high-current-carrying conductor to harvest electric power through the magnetic fields emitted by the currents in the wire. Furthermore, the right circuits could convert this power into the voltage and current appropriate for charging a small coin battery. While this feat is certainly impressive at the technical level, we wish to replicate similar results in a system that users can actually put between the plug and the wall, rather than having to take apart a cable and risk personal safety or equipment damage.

The specific choice of using inductive harvesting, rather than say capacitive harvesting, was a matter of perceived feasibility and safety. Placing anything physically between the two prongs and making contact with both, even with a dielectric, presents risks that are not necessary to take if other options are available to explore.

For wireless communication, systems which have tried to aggregate power monitoring data have traditionally relied on protocols like Zigbee. We, however, intended to use the 6lowPAN protocol, whose small packet transmission is particularly suitable for a mesh topology to extend range while conserving power, since low power consumption is exactly the goal we are trying to promote with our project.

Materials

The physical materials used by our group can be generally divided into 3 subsets:

- 1) Communication
- 2) Prototyping Circuitry
- 3) Energy Harvesting

These subsets will each be described separately in the following sections.

Communication

The main platform we used for digital processing and wireless transmission/reception was the Guidance and Inertial Navigation Assistant system, or GINA, developed by the Pister lab in order to use sensed motional data on board moving machines, such as toy electronic helicopters, to help refine the movement of those machines. As such, the GINA is equipped with sensors such as accelerometers and gyroscopes which we did not use, instead focusing on programming the microcontroller, which would receive data from an ADC, and radio, which would send packets to a hub, after which the data would be further processed and then displayed by our own software.

Prototyping Circuitry

For the actual hardware implementation of our product, our group relied by-and-large upon commercially available products, including both active and passive devices. Circuits were actually tested using fairly conventional components, such as multimeters, DC power supplies, and oscilloscopes. Occasionally, some prototyping boards were cut into smaller form factors using machinist tools such as scroll saws and Dremels.

At the “virtual” level, we used software like Multisim to actually simulate circuits and Eagle to design the final circuit boards.

Energy Harvesting

The actual energy harvesting tasks involved more specialized materials. For instance, we needed magnet wire to wrap around our cores with a large number of turns. The inductive cores themselves needed to be made of “mu-metal” sheets that were purchased from companies that specialized in making high-permeability products. We also used unconventional means, such as tape and nail polish, to protect the wire from being cut from the very act of being wound tightly and rapidly around the core.

Methodology

Previous Approach

Upon a basic dissection of the Kill-a-Watt, a representative power-monitoring technology, we discovered that it relied on a current-sense resistor, which is large and dissipates energy as heat, another large resistor intended to limit current, a safety fuse, a pair of plugs (one to take the appliance, the other to plug into the wall), and a board for circuitry to operate the display hardware.

Our hope was to make a system that is by design safe, by drawing current only as the

load requires but otherwise keeping the system at open circuit, using high-voltage-rating components where needed, and using a small radio to communicate data instead of a bulky LCD display. The intent was to reduce form factor and power draw of our device.

Design Requirements

There are two main systems which we run on our power supply: the GINA and the op-amp circuit. The GINA draws a nominal 1mA, which it is able to do after we turned off the various components not needed by our application. However, software issues still require that the GINA requires about 16mA to turn on. The op-amp sensing circuit, however, draws only a quiescent current of less than 100uA, which is required for running the highly efficient LT1078 model chip, since none of the other components in the sensing circuit are active.

The main thrust of the project, of course, was to design an inductor using hand-wound wire around high-permeability metal in the form factor that would permit a plug to penetrate the core and pin it to the wall without falling off. The intention was for such a device to scavenge enough energy from the current flowing through the plug prong that it could serve both as a power source for our circuitry and as a sensing mechanism. However, as an alternative and backup to the inductive energy harvesting method for powering the electricity consumption monitor, we had to design a circuit to take power from the electrical mains via direct electrical contact and convert it into a reliable DC supply to run GINA mote, the amplifier, and other electrical components. Either circuit would only sense current; due to time constraints, we did not explore voltage, phase, power factor, or other such quantities. The overall circuit diagram of the contact power-supply circuit as connected to the current-sensing circuit is available below (Fig. 5), where the GINA could be connected externally to the board across Zener diode D5. Given the GINA's current limitations, the contact power-supply circuit was designed to supply up to the maximum requirement of about 16mA, which folds in the relatively negligible draw from the amplifier circuit. An approximate cost for building such a circuit is calculated in Appendix A.

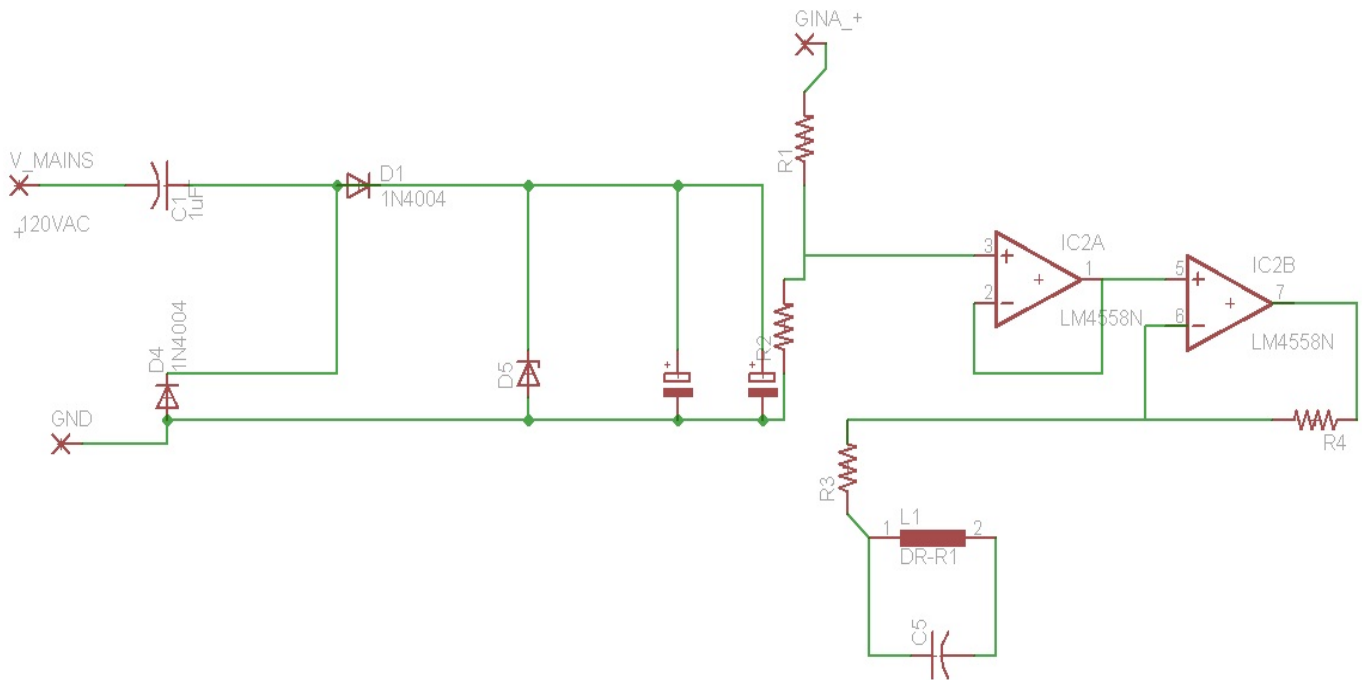


Figure 5: Contact-power supply circuit shown connected to sensing circuitry.

Current Approach

The first step taken in this effort was to consult Razavi's Microelectronics text (Ch. 3, Section 3.5.2, pg. 102) [9] for insights into the design of a rectifier followed by a fixed voltage supply. The designs in the text were functionally promising, but risked wasting too much power due to the diodes facing from the supply rail to ground, i.e. in forward-biased mode. The image below (Fig. 6) shows the topology, wherein a diode bridge is used to rectify the output of the mains, a capacitor is used to smooth the remaining AC component, a resistor is used to blunt the amount of current available to the load for safety, and a diode, or potentially a chain thereof, will maintain the load at its forward voltage, around which it deviates little with respect to variable current draw. This methodology was then scrapped, as we naturally wanted our low-power approach to simply avoid the use of dissipative components (i.e. resistors) as much as possible, not to mention the fact that a forward-biased diode simply burns current in shunt with the load without providing any useful power to it (i.e. its only function is to set the maximum

voltage available to the load).

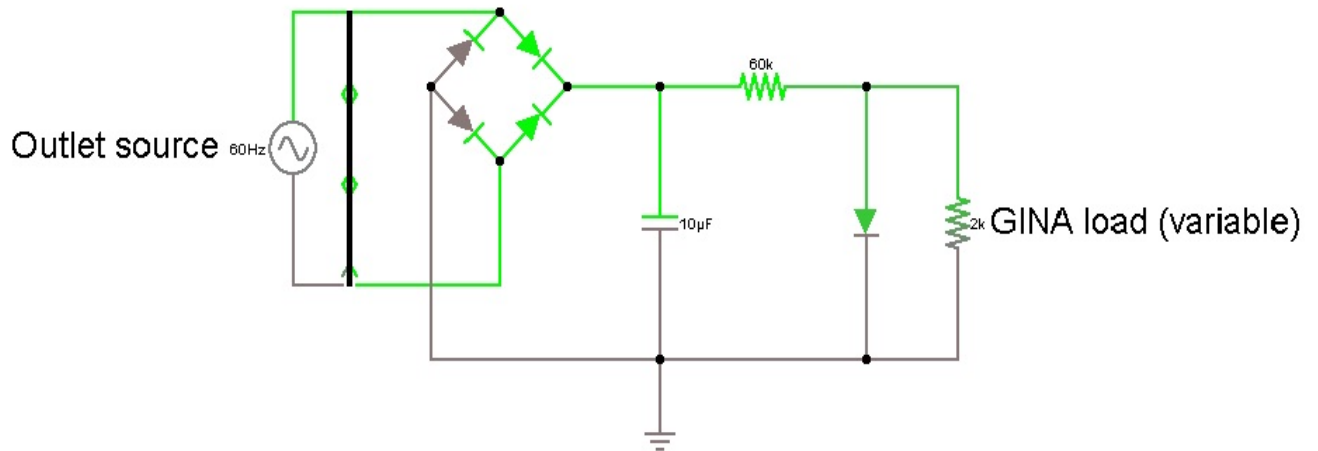


Figure 6: Inefficient Power Supply with Full-Bridge Rectifier and Forward-Biased Diode (Note: The clamping diode at the right of the above circuit is a lumped element not necessarily restricted to the usual $\sim 0.6\text{V}$ for a single p-n junction)

The design we actually used relied on a basic topology introduced by Professor Pister, using Zener diodes and a current delivery capacitor (“flying cap”) to run the requisite load. It was actually in principle a single-stage Cockcroft-Walton generator[11], a larger version of which was used to boost the output voltage of the energy harvester. The topology used in demonstration for the power supply is shown below (Fig. 7). When the electrically “hot” prong (V_{Mains}) of the plug is low (with respect to the other earth-connected prong, labeled “GND”), charge is pushed from the lower D4 (High-Voltage Rated Diode) into the terminal of the flying capacitor connected to V_{Mains} , the other 1N4004 diode preventing current from leaking out of the storage capacitors because it is reverse-biased. When V_{Mains} is high, not only is charge pushed through the capacitor from the rising voltage and into the diode (D1), but the charge that

was stored in the flying capacitor before from the low end of the cycle is also pumped through D1 into the rest of the circuit, since it is forward-biased on the high cycle of V_Mains. From here, the Zener Diode D5 clamps the voltage across it to its breakdown potential (which could safely vary between 3.3V and 5.6V, as it serves as a protection mechanism). Across this Zener diode are connected the inputs to a voltage regulator on the GINA, which down-converts the clamped voltage provided by the GINA to a steady 3V which becomes available to the rest of its circuitry. What charge flow into the GINA to run it or leak through the Zener diode is placed onto the storage capacitors, which, in the final demonstration, turned out to be 470uF each, a high value useful for limiting voltage sag due to a variable load from the GINA, which they would help supply, as well as mitigating the AC component of the output current. In testing, the GINA was replaced by a resistor equivalent to its highest current draw at 3V, its nominal supply.

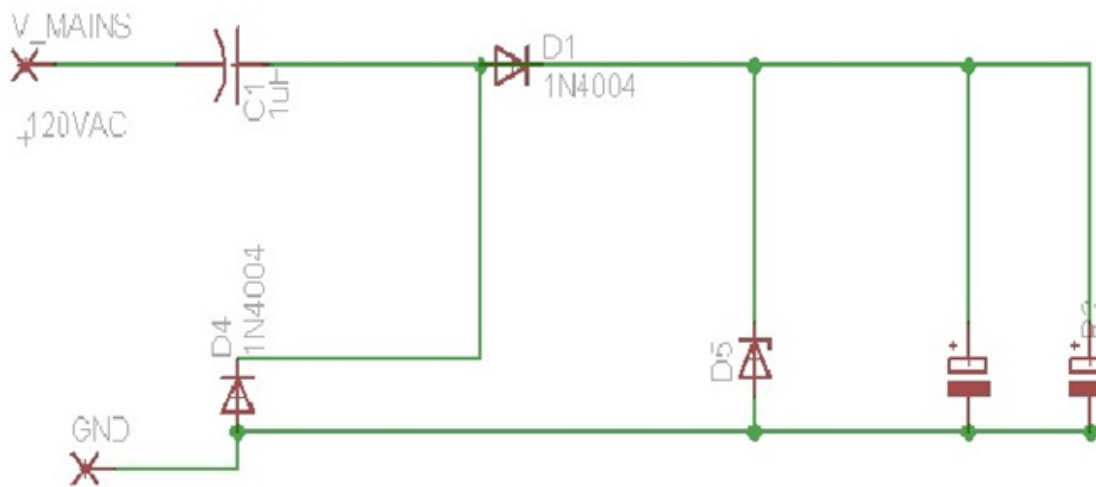


Figure 7: Contact Power Supply Circuit.

The remaining portion of the circuit is an amplifier topology (shown in Fig. 8) designed specifically to boost the current-sense signal (which will be explained in more detail below) and feed the analog data to the GINA's analog-to-digital converter.

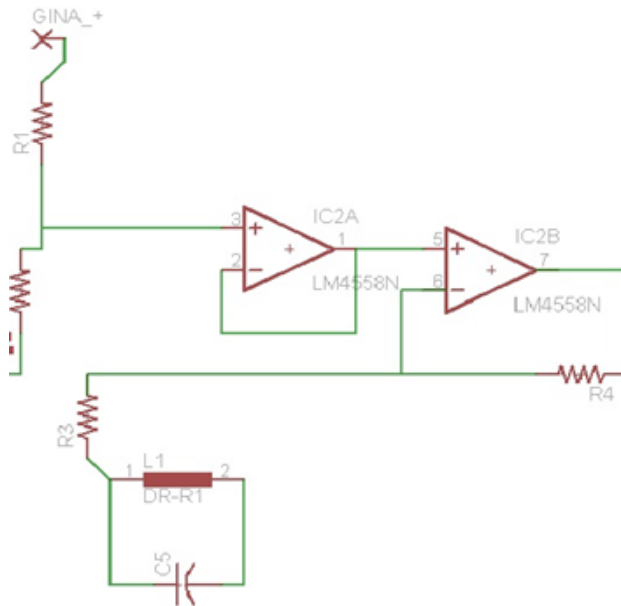


Figure 8: Current-Sense Amplifier

The first amplifier (from left to right) actually takes half of the 3V reference (divided between 2 1MegaOhm resistors, for low current draw) that is available to the ADC of the GINA, and acts as a 1.5V constant buffer in a follower configuration. The purpose of biasing the input of the second amplifier at 1.5V is to ensure that even when amplified, all current-sense signal values remain above 0V. This is necessary because the ADC cannot actually read values with negative voltages, and so will simply drop those portions of the signal. The reinterpretation of values with a voltage less than 1.5V as negative occurs in software. The gain of the second amplifier is approximately 90, as it is loaded with R4(9kOhm) and R3(100Ohm) in feedback. The choice of gain was of course determined so that the maximum detectable signal on the LC

tank will hit the most significant bits of the GINA. The choice of LC tank as a sensor is explained below.

Similar to our interest in sensing current flow using a handmade inductive transformer, we wanted to test for the contact-powered circuit whether the current flowing from a high-valued (68mH) store-bought inductor, when placed near a high-valued flowing current, would present us with a linear correspondence that could function as a current measurement to do so. To create a current that we could tune, we plugged a light-bulb into a power strip through 1) a variable transformer, in order to actually manually control the current, and 2) a Kill-a-Watt monitor to measure how much current we were actually drawing. To have a baseline measurement, we placed the inductor near the plug when the bulb was off and measured the voltage across it using an oscilloscope, just to see what the inductor would measure at “zero” current draw. After establishing the level of noise and interference using the above method, we then proceeded to measure the voltage from the inductor using the oscilloscope at various current levels, making sure to note that the waveform being measured was approximately at 60Hz frequency. The presence of the capacitor in shunt was to clean up the signal from interference as much as possible. Despite our efforts in making the current-to-voltage measurements as granular as possible, our variable-transformer had a defect whereby it would permit no current for a certain portion of its range. This problem was likely due to an internal wiring or switching problem inside the equipment that prevented a continuous range of current to flow. Having gathered what data we could, however, we then plotted the data points to obtain an approximately linear relationship between current drawn by the bulb and voltage produced by the inductor. Not only did this data tell us the slope between voltage and current using our devices, but also the amplification gain we would have to use to adequately take advantage of the GINA’s input voltage-range.

Outcomes and Findings

The main engineering tradeoff we had to make with respect to the direct-contact power supply was the capacitance ratio between the “flying” capacitor, which actually supplies the power to the rest of the circuit, and the storage capacitors. Additionally, both capacitors had to be physically limited in size, as we were aiming for a cheap, safe, small form-factor solution for the demonstration. The tradeoff arises because, on the one hand, a larger flying capacitor implies a larger available current (since $I_{\text{average}} = C_{\text{flying}} \cdot 110\text{V} \cdot 60\text{Hz} \cdot 2^{(3/2)}$) [12, but also derived in Appendix E], but also more undesirable AC ripple, since capacitors conduct more AC current for a given voltage amplitude. Of course, we should note that ripple is particularly nasty for our application since the signal we are trying to measure (plug-load current) is itself around 60Hz. To some extent, then, we needed to increase the storage capacitance, and therefore, size of the circuit, in order to reduce ripple. There is also reason to believe that a Zener diode with a steeper breakdown current-voltage characteristic would be able to tolerate AC fluctuations of current without significantly changing the voltage available to the load, and this is a potential option to explore in the future.

However, one promising avenue of progress in this regard was the reduction of power required by the GINA. If the GINA required less current, then the flying capacitor could be smaller, producing less ripple. Furthermore, the equivalent impedance looking into the GINA would be higher with constant voltage but lower current draw. This means that the capacitors in parallel would have an easier time shunting away AC current from the load. Of course, the same concerns in principle apply to loading from the amplifier circuit as well, but the LT1078 model that we used had a quiescent current less than 100uA, and thus did not present a significant concern from that perspective.

A GINA running at 1mA, even after accounting for inefficiencies, was powered by the

contact circuit with a flying capacitance of 66nF and approximately 11mV of ripple (with about 200uF of storage), quite close to the ambient interference given the frequency of the EM waves put out by the wiring of buildings. However, the circuit could only run thus after the GINA had been jump-started by a small battery. Therefore, the 1uF flying capacitance with 940uF total storage was used to actually turn on the GINA (since it requires about 16mA to turn on) and run it completely autonomously with a ripple of less than 90mV. In practice, this ripple did not significantly affect the amplifier circuit, which was able to measure a (KillaWatt-referred) 1A current draw with reasonable efficacy. In fact, an older characteristic of the inductive-sensing amplifier circuit is shown below (Fig. 9), albeit with a lower gain of about 15. The observed deviation from linear behavior that is evident in the graph deserves further investigation in future iterations of the project, but it may be a function of noise in the LC tank as a result of series resistance in the inductor lowering the quality factor, noise in the amplifier circuit, or some combination thereof.

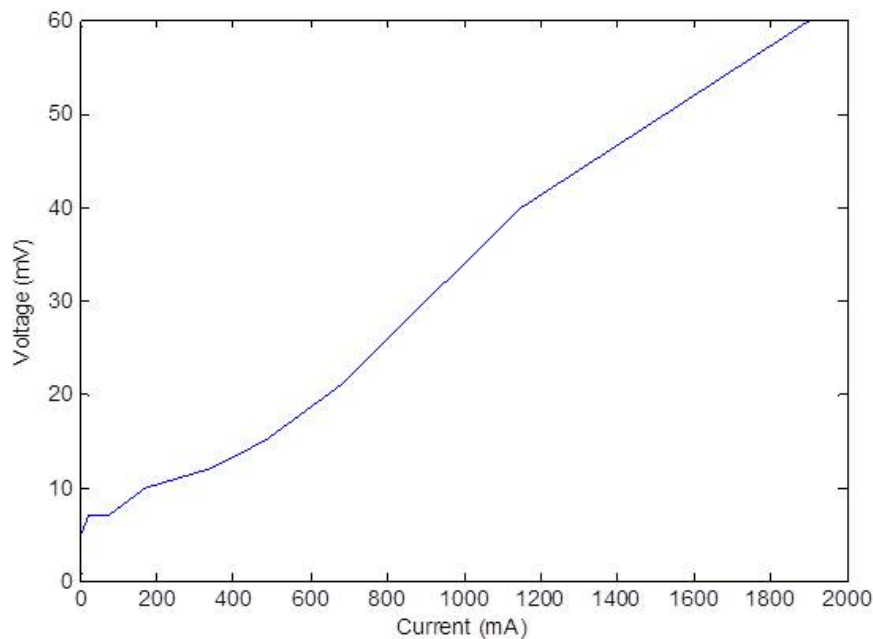


Figure 9: The relationship between load current at the outlet and amplifier-mediated sense voltage of the LC tank.

On the energy harvester side, the team was moderately successful in driving the GINA

and amplifier circuit, but, since the energy harvester was indeed an inductor, its ability to deliver power was dependent on the current load. In our case, the GINA could only run the load, after all its CW-boosting, by scavenging from a fan running at about 13A. Still, as far as the concept was demonstrated, we were successful in our goal, since the harvester also performed reasonably well as an inductor under an amplifier circuit similar to the one shown above for the contact power supply.

Conclusion

Our original goal was to develop a network-enabled plug-load power monitoring system that provided advantages of cost, power consumption, and data integration/presentation superiority over existing and likely competitors. To this end, we demonstrated two ways to perform the task of power monitoring under significant time constraints (which included a learning curve with respect to electromagnetic theory and power electronics). First, we were able to demonstrate that our handmade inductive energy harvester could both power the GINA and amplifier while acting as a sensor. Furthermore, we successfully built a mains-contact power supply circuit that could sense current and run the GINA/amplifier circuitry in a total (including external GINA board) form factor smaller than the Kill-a-Watt. We did not implement the mesh network for multiple devices, instead preferring to master the design and construction of a single (communicating) device and leaving higher-order goals to be developed on our foundation.

Future iterations in this direction, in order to better meet our goals, would have to take advantage of a few trends in technology. First among these would be the utilization of low-power radio/processor modules. If the very demand for power that our data gathering, manipulation, and broadcasting requiring lower energy harvesting efficiencies to build a working system. A related advancement that we could exploit would be the refinement of low-power protocols, which of course concerns the efficient use of whatever hardware we use. To save on

power and space, we might make more liberal use of integrated circuits in our design for specific purposes. For example, Linear Technologies has a chip, the 35881[6], that is intended exactly for converting harvested electrical energy into a proper DC supply. While the permeability of our u-metal in the inductive harvester was quite high compared to ordinary materials, it is highly likely that superior materials can be developed with which an even greater inductive harvesting can be realized. With respect to the inductive harvesting process, we may also benefit in efficiency by superior machining methods that would enable us to achieve a greater number of wire turns around the core of our secondary coil.

Assuming current trends in the cost of electrical power to ordinary consumers continues, the demand for and development of means to inform and monitor energy conservation efforts will likely follow in tow. In fact, given the increasing scarcity of clean water with respect to the growing middle class population, techniques explored in this project may be used to monitor water wastage, as buyers might be interested in saving on their running water and plumbing-related expenses. To this and perhaps even further related ends, harvesting ambient energy to power networked wireless sensors for the integration of data, as we have done here, will no doubt be an integral part of the technological solution.

Acknowledgements

The first tribute here goes to my parents, Deepa and Ajay, for their tireless efforts that have allowed me to enjoy the fruits of a world-class education here at Berkeley. After them comes my younger brother, Ankit, for whose example I strive daily to become a better man. Next, I would like to acknowledge the Fung Institute for putting together this immensely practical degree program, which has taught me much about myself, as well as the larger world of technology. Much credit goes to my project advisors, Professors Kris Pister and Bernhard Boser, for their attention, care, valuable advice (both technical and general!), funding, and constant encouragement. Professor Elad Alon deserves a special mention for willing to read my paper at the last minute and give me helpful remarks toward the final draft despite his heretofore lack of official association with the Fung Institute Program. Last but certainly not least, I would like to honor my friendly and diligent teammates, namely Vincent Lee, David Stanislawski, Ryan Moore, and Ameer Ellaboudy, who helped me greatly through this hard but rewarding endeavor.

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[17] <http://search.digikey.com/us/en/products/EMVA160ADA471MHA0G/565-2093-2-ND/756740>

[18] <http://search.digikey.com/us/en/products/GRM55DR72E105KW01L/490-3550-2-ND/789398>

[19] <http://search.digikey.com/us/en/products/5500R-686K/5500R-686KTR-ND/2686571>

[20] <http://search.digikey.com/us/en/products/C0805C185K8PACTU/399-3123-2-ND/551589>

[21] <http://search.digikey.com/us/en/products/RC0402JR-071ML/311-1.0MJRTR-ND/726409>

[22] <http://search.digikey.com/us/en/products/RC0402JR-07100RL/311-100JRTR-ND/726415>

[23] <http://search.digikey.com/us/en/products/RC0603FR-079K09L/311-9.09KHRTR-ND/727418>

[24] <http://search.digikey.com/us/en/products/PC55/PC55-ND/28472>

[25] http://www.amazon.com/P3-International-P4400-Electricity-Monitor/dp/B00009MDBU/ref=sr_1_1?ie=UTF8&qid=1336732428&sr=8-1

[26] <http://search.digikey.com/us/en/products/BZX84-C3V3.215/568-1675-2-ND/763279>

[27] <http://search.digikey.com/us/en/products/ECE-V0GA101SR/PCE3054TR-ND/226911>

[28] <http://search.digikey.com/us/en/products/C3216X7T2W104K/445-7758-2-ND/2733193>

[29] <http://search.digikey.com/us/en/products/ISL28194FHZ-T7/ISL28194FHZ-T7TR-ND/1787071>

[30] <http://search.digikey.com/us/en/products/NL565050T-103J-PF/445-3666-2-ND/1856431>

Appendix A: BOM

The below tables indicate bills of materials that would accrue for redoing (left half) the prototype contact power supply circuits with surface-mount components (cost of board and GINA are neglected here, as both were prototyping platforms not representative of plausible product) as well as those for building (right half) a more optimized version closer to commercialization, in which the digital circuits never require more than 1mA. This should be compared with the approximate \$20 price-tag [25] of the Kill-a-Watt.

Power Supply

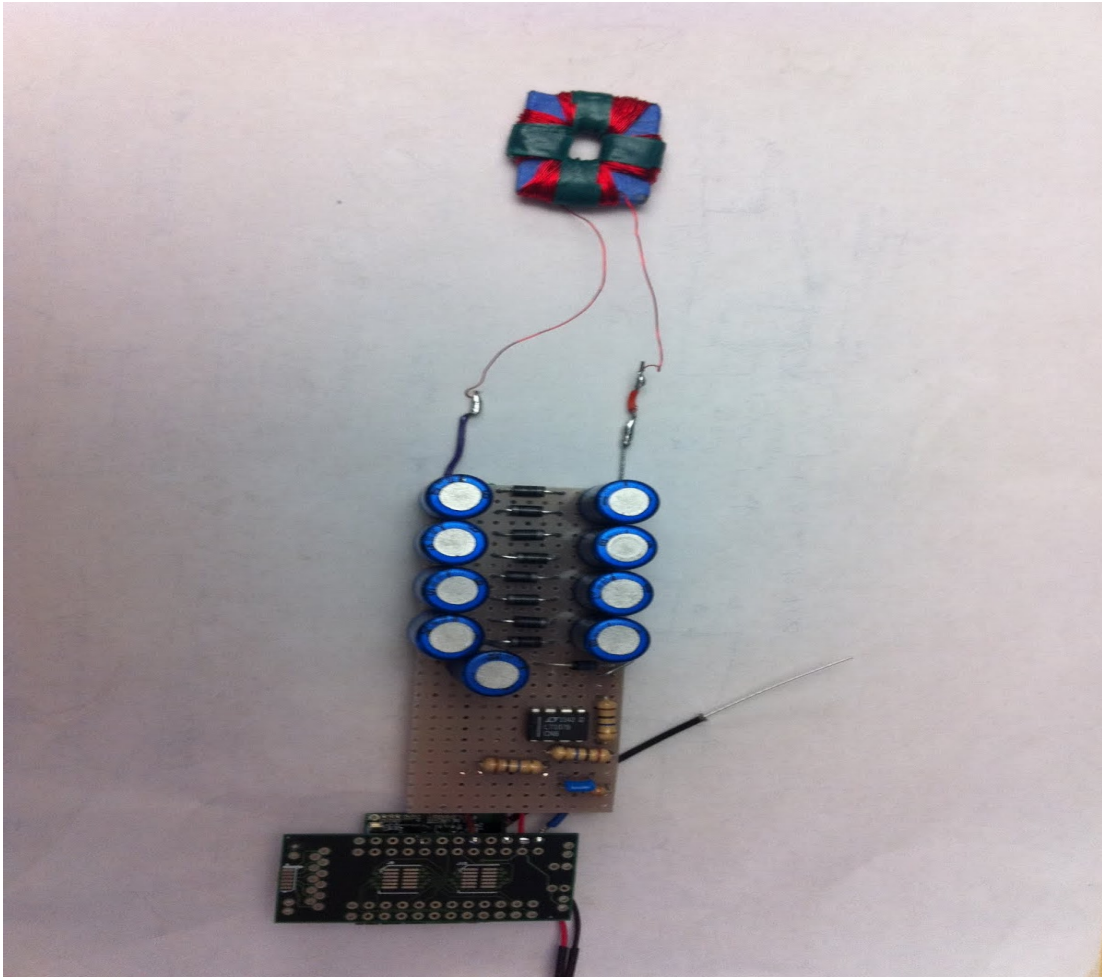
Item (in Prototype)	Quantity	Bulk Cost per Unit	Cost per Circuit	Item (in Future Iteration)	Quantity	Bulk Cost per Unit	Cost per Circuit
LL4148FST R-ND Diode (D1, D4, replacing 1N4004)	2	\$0.01 [14]	\$0.02	LL4148FST R-ND Diode (D1, D4, replacing 1N4004)	2	\$0.01 [14]	\$0.02
DL4729A-TP (Zener Diode)	1	\$0.10 [15]	\$0.10	BZX84- C3V3,215 (Zener)	1	\$0.02[26]	\$0.02
A100751CT- ND (Contact Brushes for Mains, needlessly expensive)	2	\$0.20 [16]	\$0.40	Homemade Metal Contacts	2	<\$0.01	\$0.01
EMVA160AD A471MHA0G (Storage Caps)	2	\$0.12[17]	\$0.24	ECE- V0GA101SR	1	\$0.07 [27]	\$0.07
GRM55DR72 E105KW01L (Flying Cap)	1	\$0.31 [18]	\$0.31	C3216X7T2 W104K	1	\$0.07 [28]	\$0.07

Total			\$0.95	Total			\$0.19
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Sensing Circuit

Item (in Prototype)	Quantity	Bulk Cost per Unit	Cost per Circuit	Item (in Future Iteration)	Quantity	Bulk Cost per Unit	Cost per Circuit
LT1078 Op-Amp	1	\$3.65 [13]	\$3.65	ISL28194FH Z-T7	3(1 for buffer, 2 for amp)	\$0.89 [29]	\$2.67
5500R-686K (68mH Sensing Inductor)	1	\$2.81 [19]	\$2.81	NL565050T-103J-PF (10mH)	1	\$0.29 [30]	\$0.29
C0805C185K8PACTU (1.8uF in shunt with inductor for noise reduction)	1	\$0.06[20]	\$0.06	C0805C185 K8PACTU	1	\$0.06 [20]	\$0.06
RC0402JR-071ML (R1, R2)	2	<\$0.01 [21]	\$0.01	RC0402JR-071ML (R1, R2)	2	<\$0.01 [21]	\$0.01
RC0402JR-07100RL(R3), RC0603FR-079K09L (R4)	2	<\$0.01 [22, 23]	\$0.01	Feedback Resistors	4	<\$0.01	\$0.01
Total			\$6.54				\$3.04

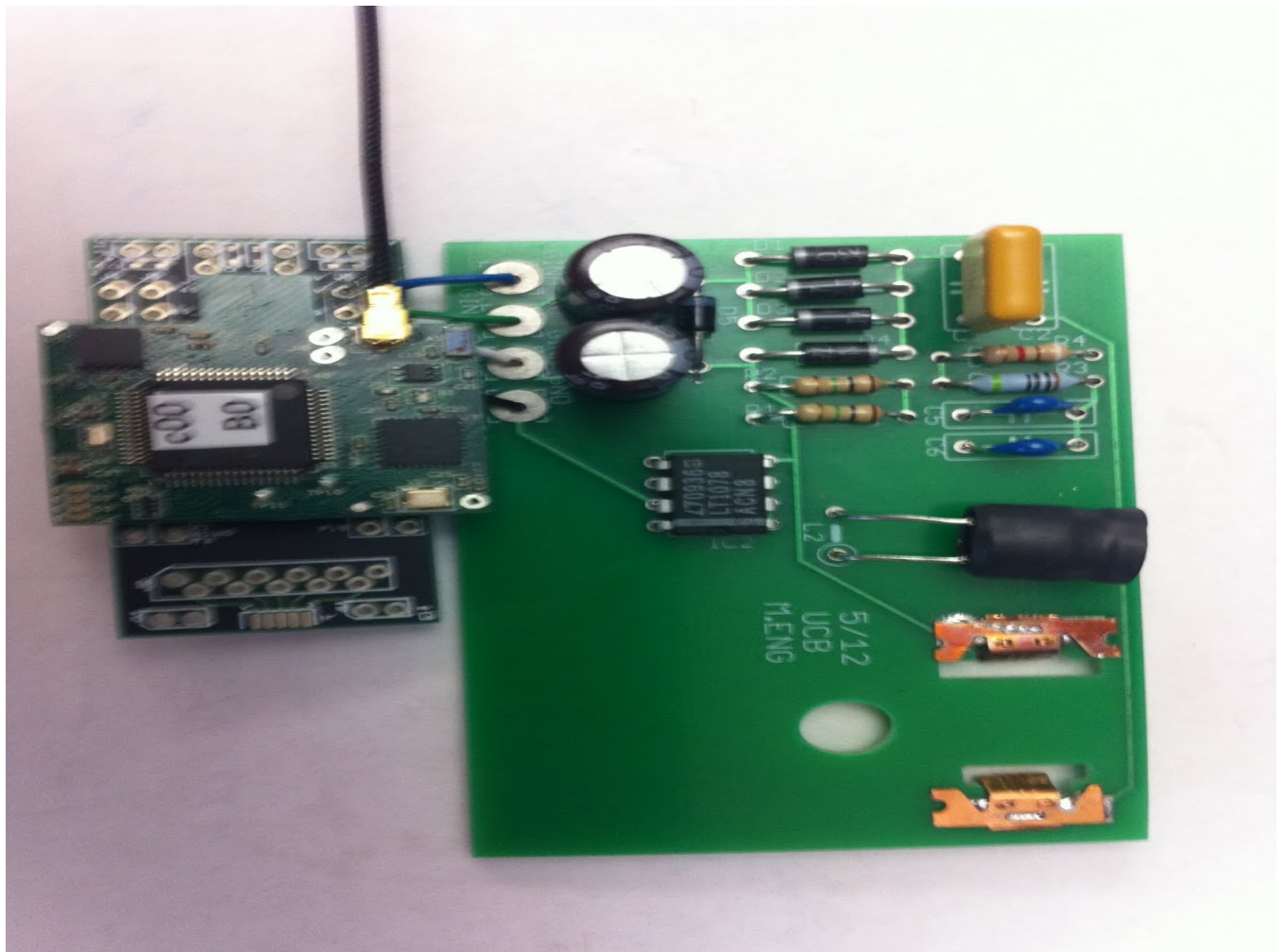
Appendix B: Harvester Circuit



Pictured above is the actual physical implementation of the Energy Harvesting/Sensing circuit, with the transformer as the uppermost object, covered in wire and colored electrical tape (for protection), the Cockcroft-Walton generator for voltage boosting, indicated by the bank of large capacitors, the amplifier at the bottom of the first board, and the GINA mote at the very bottom.

Appendix C: Contact Circuit

Shown below is the circuit-board that makes direct contact with the mains, rectifying and stepping down the voltage to power the GINA and amplifier. Most components here were commercially available and hand-soldered onto the board, though the PCB itself was custom-designed and manufactured.



Appendix D: Kill-a-Watt

Courtesy of P3 International, the manufacturers of the Kill A Watt



Appendix E: Derivation of Average Current

During the part of the cycle at which V_{mains} is less than ground, diode D4 is forward biased, shorting the “right” plate of the flying capacitor to ground and giving this capacitor a negative voltage looking left to right from V_{mains} to the rest of the circuit. Charge builds on the capacitor until the sinusoid reaches a trough at $-110\sqrt{2}$ Volts, or approximately -155V. As V_{mains} approaches 0V again, diode D4 and D1, not counting any leakage current prevent any charge from leaving the right plate of the flying capacitor, maintaining the $-110\sqrt{2}$ Volt drop. As V_{mains} rises above the ground voltage on the positive half of the cycle, diode D4 enters a state of reverse-bias, isolating the right plate of the flying capacitor from ground, as D1 becomes forward-biased, taking positive charge from the right plate of the flying capacitor and depositing it into the Zener diode, the load, and the storage capacitors. Neglecting any limitations imposed by the Zener diode, the flying capacitor eventually reaches a positive voltage peaking at $110\sqrt{2}$ Volts from left to right. This implies that the sign of the charge on the right plate of the capacitor is now negative. In short, the charge on that plate changed from $C \cdot 110\sqrt{2}$ Coulombs to $-C \cdot 110\sqrt{2}$ Coulombs within the $1/(60\text{Hz})$ period, where C is the capacitance of the flying capacitor. Therefore, the average current supplied by the circuit is approximately $2 \cdot C \cdot 110\sqrt{2} \cdot 60\text{Hz}$, not accounting for non-idealities in the diodes.