Eco-Home

Wireless Communication System

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"If you want to 1 year of prosperity, plant corn.  
If you want 10 years of prosperity, plant trees.  
If you want 100 years of prosperity, educate people."

- Chinese Proverb

**Motivation and Objective**

How much power is the washing machine using at the end of the year? How much does it cost to enjoy a hot shower every morning? This project will answer such questions by implementing a system that measures the power each appliance is using. The system will report these power readings wirelessly to a central monitor device, in this case, a laptop with a receiver. The information is then processed and the user is able to interact with the results and able to interpret them. Once this system is implemented it might lead to new ideas for sustainable technologies for a greener planet.

In recent years, people around the world have started to think twice about how we are depleting the earth’s resources to satisfy our thirst for energy. Due to concerns such as global warming, we have now been introduced into a new era: the “think green” era. Saving energy at home is the first step to going green. EcoHome is a system designed for a homeowner to have the ability to know exactly where the most electricity is being used around his or her home. With sensing devices integrated in most commonly used appliances around the home, EcoHome will allow people to take control of their home’s power consumption. It allows this by providing them with specific power usage reports, recommendations, and, most importantly, it will open a new door into the world of appliance-to-appliance communication and appliance control to save energy and money.
Overall Implementation

The project is structurally divided into two main stages; the hardware and software stages. The hardware part consists mainly of a power monitoring circuit which was constructed using Low-offset Low-Drift Operational Amplifiers, an analog multiplier chip, and some basic passive components. The software part also contains hardware parts that make wireless data possible via XBee technology. Other software is also involved and will be described in more detail within the corresponding section in the following part. The following figure shows the testing equipment used, with a number which identifies them in order to provide its full name and a small description of why and how it is being used. Alternatives for different devices and technologies will also be mentioned within the corresponding stage in the hardware and software sections.
Device 1: Variac Variable Transformer 3PN1010B: The purpose of the Variac is to have a variable voltage control in order to have more realistic testing simulations.

Device 2: Isolation Transformer 23V367 (500VA – 115V – 50-60Hz): Used to isolate the actual earth ground and create a floating virtual ground for safety reasons.

Device 3: Kill-A-Watt P4400: A power measuring device used as a reference and easy voltage readings when changing the voltage with the variac. Accuracy of the Kill-A-Watt not calculated.

Device 4: Line/Load Box with capacity to measure two different loads at once.

Device 5: Main Breadboard with Circuit Design (EIC-104-1).

Device 6: Tektronix DPO 3012 Digital Phosphor Oscilloscope: Used to measure and display our output readings, phase shifts on capacitance/inductive loads, trouble shooting tool.

Device 7: Tektronix TM 503 Function Generator: Used to power up chips on the circuit and the arduino board.

Device 8: Arduino Board with XBee shield and Xbee chip (Transmitter.)

Device 9: Agilent 34405A 5 ½ Digital Multimeter: Use to measure different voltages and currents. Mostly used for the 120V AC voltage and current readings.

Device 10: USB Explorer with XBee (Receiver.)

Device 11: Main Computer with software to compute user end results.
**Hardware: Current Sensing and Power Calculation**

**Design Specifications**

As explained in the previous section, our project consists of two parts, the hardware portion and the software portion of the project. Consequently, in order for the project to be completely functional, we must meet certain criteria that the software group will need. First, the arduino boards are sensitive to the voltage applied; they are designed to operate within a range of 0-5V DC for their analog inputs, anything higher than that would burn out the board. Second, the board is not compatible to recognize negative voltage; therefore any negative outputs will not be recognized by the board.

Because of the requirements our goal was to provide a circuit that could handle loads from a range of 0W to 2500W as an input, and have a positive output of no more than 5V DC. The 2500W was chosen because a typical appliance will be connected to a 20 amp circuit breaker in your electrical panel.

\[
\frac{2500W}{120V} = 20.83 \text{ amps.}
\]

In reality, the appliances in your home will operate at less than 15 amps. Anything higher than 20 amps, will most likely be connected to a 220V line. For example a hot water heater or an AC Condenser.
Early Problems

![Diagram of a power consumption meter](image)

**Fig 1. A Power consumption meter (Source 1)**

The initial proposed idea was using the diagram above; which uses a signal obtained from the magnetic field created by the 120V alternating current. The idea is to place a toroid transformer around the hot line in order to induce a secondary alternating voltage which will be proportional to the primary current being used.

$$P_{\text{incoming}} = I_P V_P = P_{\text{outgoing}} = I_S V_S$$
The challenge came when it was time to separate the voltage and the current signals in order to measure power, it turns out that the voltage generated is based on the primary current, making it difficult to calculate anything other than resistive loads. Even with resistive readings taken, the circuit showed many inconsistencies between different loads. Another issue was picking up low current devices; for example an 20W device, will produce a current of about 0.166 amps, this low current was very difficult to pick up in the secondary side.

**In-line approach**

![Diagram of 120 V Wattmeter](image)

**Fig 2. A Practical Wattmeter (Source 2)**

The in-line approach is a much simpler design which involves plugging a device into the wall outlet. Because of this simplicity it was the preferred method to use for our project. The circuit used is shown in Fig. 2. This implementation will actually take the power factor of capacitance and inductive loads into account to produce an accurate reading regardless on the type of load. The first thing we will notice is a “Voltage Divider” circuit created by the 330K and the 20K resistors:
This will lower our voltage to about 6.85V

\[
\frac{330K}{20K + 330K} \cdot 120V = 6.85V
\]

The second part of the circuit consists of a 10Ω resistor; this is a current sensing resistor. Because of the low voltage output requirements of no more than 5V, the resistor was reduced to 0.01Ω in order to scale down the circuit to stay within the required output voltage. This low resistance was achieved by simply having a 2 ft. piece of 14 AWG copper wire. Depending on the load connected to the circuit, this resistor will sense a current which will lead back to the neutral side of the transformer. By simply using Ohm’s Law \( V = IR \) one can see that as the current changes, there will be a variable voltage. The voltage obtained across this resistor will then be taken through a differential amplifier with a gain of 17. At this point, the voltage signal from the current divider and from the sensing resistor will be going into an AD633 chip; this is an analog multiplier, its function is to multiply the two input signal, then it will lower the value by a factor of 10 (1/10V), and finally integrate the signal.
The output of the AD633 will be a DC signal, however the last step is to pass our signal through a Low Pass Filter, in order to reduce the noise and clean out our signal.

The output of this circuit is a voltage lowered by a factor of 1000. Notice the diagram states 1vw. This simply means that 1 V = 1W. In our case a 100W load will have an output of 0.1vw or 100mV

Another important factor will be the calibration of the circuit, because of the load the circuit consumes, the readings are actually about 30mV higher than the actual readings. Calibration will be handled through the software in the arduino board in order to simplify things. The calibration methods will be discussed in the software section.

During the calibration testing, it was noticed that the circuit is actually temperature dependent. The AD633 and the LF411 chips are only accurate after a 30 minutes warm up period. The group did not have the time to find a solution to this problem, but further consideration in the issue is recommended.
Implementation (Cost, Details and Design)

Cost

The price of building the actual circuit was very low, with the highest price being the AD633 which runs for $5.02 each. The rest of the components were picked up at our ECE Labs and their price range is in the order of cents.

Readings

Actual readings were taken which included resistive, capacitance, and inductance loads. Our circuit performed with a very low percent error during each test. Notice that more than one light bulb of the same wattage was tested and our circuit remained consistent. During the 20W CFL test, which is a capacitance load, it was proven that our circuit is in fact taking into account the power factor shift between the current and voltage sinusoidal signals.
<table>
<thead>
<tr>
<th>100W Lightbulb</th>
<th>60W Lightbulb</th>
<th>20W CFL*</th>
<th>RC Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>120.63</td>
<td>120.63</td>
<td>120.63</td>
</tr>
<tr>
<td>Current</td>
<td>0.84</td>
<td>0.51</td>
<td>0.35</td>
</tr>
<tr>
<td>Watts</td>
<td>101.69</td>
<td>61.28</td>
<td>42.22</td>
</tr>
<tr>
<td>Wattmeter Output</td>
<td>0.13</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>Actual Reading</td>
<td>101.47</td>
<td>61.14</td>
<td>23.32</td>
</tr>
<tr>
<td>Percent Error</td>
<td>0.22</td>
<td>0.22</td>
<td>10.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>100W Lightbulb</th>
<th>60W Lightbulb</th>
<th>Computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>120.63</td>
<td>Voltage</td>
</tr>
<tr>
<td>Current</td>
<td>0.86</td>
<td>Current</td>
</tr>
<tr>
<td>Watts</td>
<td>103.26</td>
<td>Watts</td>
</tr>
<tr>
<td>Wattmeter Output</td>
<td>0.13</td>
<td>0.08</td>
</tr>
<tr>
<td>Actual Reading</td>
<td>103.03</td>
<td>61.69</td>
</tr>
<tr>
<td>Percent Error</td>
<td>0.22</td>
<td>0.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>100W Lightbulb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Watts</td>
</tr>
<tr>
<td>Wattmeter Output</td>
</tr>
<tr>
<td>Actual Reading</td>
</tr>
<tr>
<td>Percent Error</td>
</tr>
</tbody>
</table>

* Inductive load, includes a phase shift error

**Resistive loads vs. Energy Storage Components**

Using an RC circuit as a load we were able to show the behavior the circuit under a non resistive situation. During this test, we were able to show that the circuit calculates power accurately for the devices with phase difference. The phase shift of the circuit is shown in the videos included. A 55Ω resistor and 5uF capacitor used to create the phase shift. The connection was done in series, and here it was shown that only the resistive loads actually consume power, the capacitor is only an energy storage component; therefore, it should not consume any power.

The current in the circuit is

\[ I(s) = \frac{V_{in}(s)}{R + \frac{1}{Cs}} = \frac{CS}{1 + RCs}V_{in}(s) \]

The current which was going through the circuit was 0.0232008177 + 0.223789383i and when we calculated the power with our current and squaring it and multiplying with the resistance, which is 55 ohms, comes out to be -2.72488755 + 0.571130635i t

When we saw the circuit output moved from initial voltage 8mv to 11mv which with our multiplier, which was 0.78125 came out to 3V.
Conclusions, Error Analysis and Data Interpretation

The hardware part of the project was a success; many of the initial problems were overcome by taking a different approach and eliminating the problems all together. The simplicity of the linear circuit made it possible to troubleshoot the circuit step by step, in order to have a good understanding of what is happening along the entire circuit. Good testing equipment was used and safety concerns were dealt with appropriately to avoid any accidents with the 120V AC voltage readings. Overall, very good progress was accomplished with some minor improvements that could be considered in the future, such as adding thermal components, in order to eliminate accuracy errors due to cold temperatures. The accuracy achieved by our circuit after the appropriate warm up period was less than 5%.
## Hardware Parts Used

<table>
<thead>
<tr>
<th>Qty</th>
<th>Device</th>
<th>MRSP Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3PN1010B Variac Variable Transformer</td>
<td>$333.00</td>
</tr>
<tr>
<td>1</td>
<td>Isolation Transformer</td>
<td>(borrowed)</td>
</tr>
<tr>
<td>1</td>
<td>Kill-A-Watt P4400</td>
<td>$22.49</td>
</tr>
<tr>
<td>1</td>
<td>Tektronix DPO 3012 Digital Phosphor Oscilloscope</td>
<td>(borrowed)</td>
</tr>
<tr>
<td>1</td>
<td>Agilent 34405A 5 ½ Digit Multimeter</td>
<td>(borrowed)</td>
</tr>
<tr>
<td>1</td>
<td>Tektronix TM 503 Function Generator</td>
<td>(borrowed)</td>
</tr>
<tr>
<td>1</td>
<td>Main BreadBoard with Circuit Design (EIC-104-1)</td>
<td>(borrowed)</td>
</tr>
<tr>
<td>1</td>
<td>Load/Line Box with capacity to hold two devices at once</td>
<td>(bought)</td>
</tr>
</tbody>
</table>

### Other Devices with negligible price:

<table>
<thead>
<tr>
<th>Qty</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Low Cost Analog Multiplier (AD633AN)</td>
</tr>
<tr>
<td>4</td>
<td>Low Offset, Low Drift JFET Op Amp (LF411C)</td>
</tr>
<tr>
<td>2</td>
<td>Operational Amplifier (LM741)</td>
</tr>
<tr>
<td>2</td>
<td>1 µF capacitor</td>
</tr>
<tr>
<td>6</td>
<td>100 KΩ Resitor</td>
</tr>
<tr>
<td>4</td>
<td>68 KΩ Resitor</td>
</tr>
<tr>
<td>2</td>
<td>2 KΩ Resitor</td>
</tr>
<tr>
<td>2</td>
<td>330 KΩ Resitor</td>
</tr>
<tr>
<td>2</td>
<td>20 KΩ Resitor</td>
</tr>
<tr>
<td>4</td>
<td>100 Ω Resitor</td>
</tr>
<tr>
<td>2</td>
<td>3.9 KΩ Resistor</td>
</tr>
</tbody>
</table>

Other elements where used to do the calibration as well such the Rex Rheostat (57Ω – 2.8A) and a RC simple circuit.
Software Part: Wireless Communication

XBee Board Elements:

Fig 2. Arduino Board, XBee Shield and XBee (Transmitter)  
Fig 3. USB Explorer with XBee (Receiver)

The Transmitter and its three main parts

Fig 4. Arduino Duemilanove Board: This is the main board where the power signal received from the breadboard is processed through the programming code which is stored within the Arduino Board.

Fig 5. XBee Shield: The shield is the bridge that communicates with the XBee chip.

Fig 6. XBee Chip: This chip takes the power signal reading and sends it wirelessly to the receiver which is connected to the computer.
The receiver and its two main parts

**Fig 7.** XBee chip: This chip receives the power reading sent from the other XBee chip and stores it in the computer via mini-USB cable.

**Fig 8.** USB Explorer: This is the bridge which allows the XBee chip and the computer software to communicate.

Implementation (Cost, Details and Design)

**Overall Design**

As the team put together the various parts of this software side, a few alternatives were considered, such as the use of Bluetooth. Even though Bluetooth provides a good range, it uses more power and might conflict with other devices around the house in the same frequency levels. The team then considered XBee which has a greater range while utilizing even less power (2mW) for about ~120 meters with a 2.4GHz antenna while Bluetooth uses 100mW for ~100 meters. The following table describes the range of Bluetooth.
The design of the hardware elements as a whole body were easy to assemble and the restrictions imposed by the devices were not high enough for the group to be able to work with such restrictions. The power supply for the Arduino Main Board needed 5V, which was easily provided by the Function Generator. The XBee shield and XBee mounted perfectly on the Arduino Board making wireless communication possible for multiple transmitters and a single receiver. The XBee chips were programmed as either a Receiver (Router AT) or a Transmitter (Coordinator AT) using a small software called X-CTU.

Using a USB Explorer attached to XBee receiver chip via mini-USB cable, the data for the power readings were then read from a small software called putty. This data was then logged into putty which was able to store the data continuously as the data was being received.

Matlab was also a good tool for programming the code by importing the data from a text file generated by putty. Matlab can then calculate how much power the appliance uses, how much $ KWh will cost the end user, an estimate monthly average and so on. The user is also able to detect if any appliance is consuming more power than the normal stipulated value that can be read from the back of the appliance where the standard power consumption is printed. Matlab also enabled the team to create a full interactive and comprehensive GUI (Graphical User Interface) for the end user to be able to analyze, compare and view results and open doors for the future; for example, having the ability to power off the appliances an iPhone application if they are
consuming too much power. The following table depicts the costs of the software devices implemented in the project.

**Cost**

<table>
<thead>
<tr>
<th>Software Parts</th>
<th>Qty</th>
<th>Device</th>
<th>MRSP Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>Arduino Main Board (Duemilanove &quot;2009&quot;)</td>
<td>$29.95</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>XBee Shield</td>
<td>$24.95</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>XBee 2mW Series 2.5 U.FL Connection</td>
<td>$25.95</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>XBee Explorer USB</td>
<td>$24.95</td>
</tr>
</tbody>
</table>

**Hindsight Design Considerations**

In retrospect, we could have considered minor changes to the design specifications for the software part of the project. Firstly, we could have changed the baud rate of our serial connection. At the moment we are using 9600 baud which is high. We are only transmitting a maximum of 1024 bits every two seconds. So we do not need to open up the connection at 9600 baud. 1200 baud would do just fine for our purposes.

Also, we use Matlab to store all the values read from the xbee and perform calculations. These calculations can be performed on the arduino board itself. The processor speed on the arduino board is 16MHz. This processor is powerful enough to calculate the averages and then transmit them such that they can be stored on the server. This way, the end user does not need to purchase a separate software like Matlab. This also makes the entire system universal to PC, MAC, Linux, and etc.
Another alternate design consideration is the number of devices that could be connected to one xbee router. For the purposes of the project we built a network of two devices. In other words, the end user can use this system for two different appliances. But, an average household can be the home of several appliances. The question becomes: how many devices can be connected to one router at the server. After further reading, we found out that the answer is 10-12. But what if a household has more than 12 appliances? Or, what if a user wants to monitor more than 12 appliances? If that is the case, then one would need to create different subnets to accommodate for the extra devices and appliances. So if a user wants to monitor 18 appliances, then they would need to create two different subnets with 9 devices each; or however the user wishes to create a subnet.

We need to acknowledge the fact that there will be packet collisions. If two or more devices in the same subnet are sending a packet to the router at the same time, only one will make it through. This issue can be solved because the xbee protocol has its own collision detection system. If two devices send a packet at the same time, then the receiver will randomly choose to receive a certain packet, and then it will receive the other. This way, there are no collisions, and all the packets are received appropriately.
Conclusions, Error Analysis and Data Interpretation

The data obtained at first was very incoherent; the readings were very random and inconsistent. The team then realized with the help of our advisor that the Arduino board was not properly grounded. The board was powered through the usb cable which was plugged into the laptop. The laptop itself has several internal impedances within itself. We then powered up the Arduino board with 5V DC input instead of using the laptop USB. After doing so, the data started making more sense however the readings were in the range of 0 to 1024. We had to multiply the readings with the ratio set up such that a 0 would mean 0V and a 1024 would mean 5V. After converting the reading into the appropriate reading that represents power, we had to calibrate such that a 100W light bulb would show close to 100W. The team then moved on to adjust the readings based on readings from different loads and repeated loads, for example, a few 100W light bulbs, microwave, laptop, etc. The calibrated numbers were inputted and coded into Arduino Board similar as to when the reading gets delivered to the receiver; it reflects the real calibrated value to show expected values. Using multiple loads of the same type, such as a few 100W bulbs helps to decipher the real calibrated multiplier value since not all bulbs are the same in actually.
By analyzing these values the end user can easily interact with the Matlab GUI design and interpret results which could potentially describe a malfunction with an appliance and the user will be able to determine which appliance is making his or her electric bill so high.

**Future Applications**

While designing this project the idea of being able to create a network of appliances that are able to talk among each other was a possibility. Now that the project is completed the group can see this idea happening in the future.

**Conclusions**

Overall, this project was intended to give the average user a better idea of how much power their appliances are using around their household. The software side of the project included transmitting the power reading from the appliance to the main hub where all the readings could be stored. Not only were the readings stored in the main hub, but the readings used to calculate the average and display it to the user in a nice, versatile GUI. By doing so the user is able to determine what appliances are consuming a lot of power and then is able to take alternative actions to reduce his or her power consumption. All these ideas lead to the main objective which is to save power for a greener world.
References

Source 1: Power Consumption Meter

Source 2: A Practical Wattmeter
http://mysite.du.edu/~etuttle/electron/elect64.htm

Source 3: Informational Reference
http://www.google.com/patents?hl=en&lr=&vid=USP4T5315236&id=Wad7AAAAEBAJ&oi=fnd&dq=power+meter&printsec=abstract#v=onepage&q=&f=false

Source 4: RC circuit analysis
Appendix

RC Circuit

Phase Difference

Initial RMS value with nothing connected (4.50mV)
RMS Value After the circuit was connected (8.47mV)