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Home-Based Power Outlet Consumption Monitoring System

Jirro De Guia, Troy Driver, Reynaldo Olanday, Arvin Reyes and Clement Ong*
Computer Technology Department, College of Computer Studies, De La Salle University
*clem.ong@delasalle.ph

Abstract: Our reliance on dwindling fossil fuels and increasing power generation has made the conservation and conscientious reduction of energy use of much greater importance today. While household appliances are increasingly more energy efficient, a household has a plethora of personal electronic devices (gadgets) for each member of the dwelling. The typical end-result is a monthly electric bill that leaves the question of where all the kilowatt-hours has gone.

This paper presents a system capable of monitoring and consolidating information regarding the energy consumption of individual appliance. The individualized power monitors are accurate to within one percent, and capable of measuring instantaneous wattage and volt-ampere. The consumption is aggregated and sent through the powerline to a central database, where a web-based client software reports and plots appliance consumption.

The system uses encryption to provide the necessary data security. The power monitor was tested on appliances varying in power from 3.5W to 1300W. Stress-testing by use of appliances rated from 180W to 1300W, carried out over a continuous three (3) day period verified the reliability of the system, while a survey showed that the user –interface software was easy to understand and useful.

Key Words: Efficiency; Energy; Feedback; Power, Smart Power

1. INTRODUCTION

This work offers a simple solution to the growing power needs by raising the awareness of homeowners regarding how much individual household devices are consuming electricity. Users will be able to determine, for example, the cost effectiveness, efficiency and truthfulness of manufacturer's claims and specifications. By doing so, homeowners will be empowered to consciously reduce power usage as well as possibly be alerted to underperforming or problematic appliances and devices.

2. SYSTEM OVERVIEW

The Home Based Power Outlet Usage Monitoring System consists of one or more power monitoring devices and a server to store the data that has been recorded by the power monitoring devices. This project involves monitoring and recording the energy consumption of one or more household appliances, the storage and display of the information in an organized manner and finally, the transmission from the power monitoring device to the server, which will involve power line communication technology.

The consumption of any appliance or device to be monitored is achieved by placing the monitor between the the appliance and the power outlet. Data is sent through the power lines as soon as the server broadcasts a request, or being manually requested by the homeowner, in which commands the power monitoring devices to begin sending their recorded data to one device at a time. Once the server has received the information, it will organize the information and display the data in its web-based interface for the homeowner to view.

2.1 Power Measurement Module

The power measurement module is located in the power-monitoring device, where it interfaces the household appliance with the network interface module and the power outlet as seen in Figure 1.

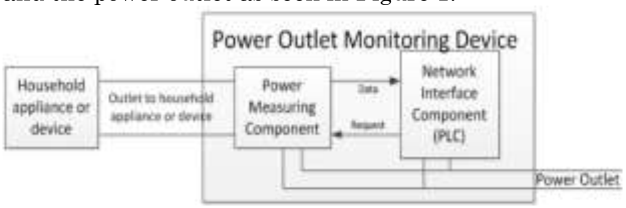

Fig. 1. Power Outlet Monitoring Device Diagram

Its main purpose is to monitor and record the Watts, Apparent Volt-Ampere (VA), Volt-Ampere Reactive (VAR), Power Factor (PF), Voltage (VOLT), and Ampere (AMP) of the interfaced appliance. Once the interfaced appliance consumes power the POWER indicator will then turn on. Communication (COM) indicator will start to flash every time new data is transmitted or acquired. The data will be transmitted, in Comma Separated Values (CSV) form, through the TTL UART compatible serial port [3].

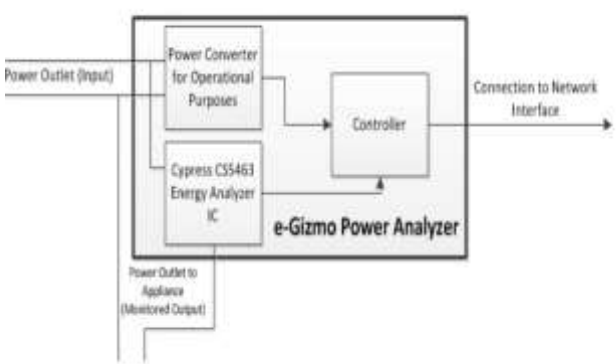

Fig. 2. Power Measurement Component Diagram

In Figure 2 it is seen, in the upper left corner, that the power outlet is used as its power source. The core measuring part is shown in the diagram as one line that goes directly to the power outlet output to the appliance, while the others would go through the energy analyzer IC. In the IC, the power consumption of the appliance will be measured and sent to the controller, once requested.

2.2 Network Interface Module

The network interface consists of a transmitter/receiver component that is compatible with the X10 protocol. The microcontroller contains the X10 protocol functions, encoding/decoding and interfacing with the power measuring component.

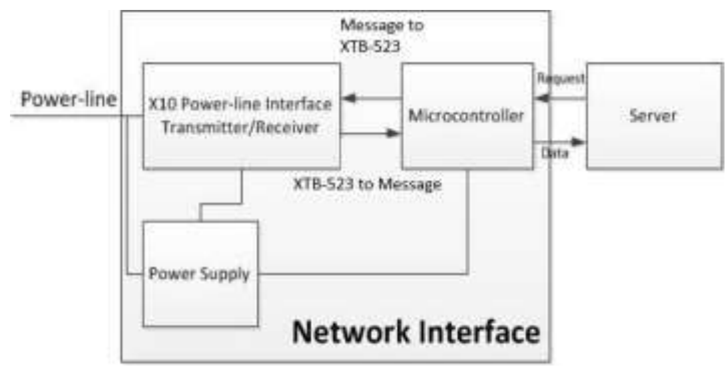

Fig. 3. Server-side Network Interface Block Diagram

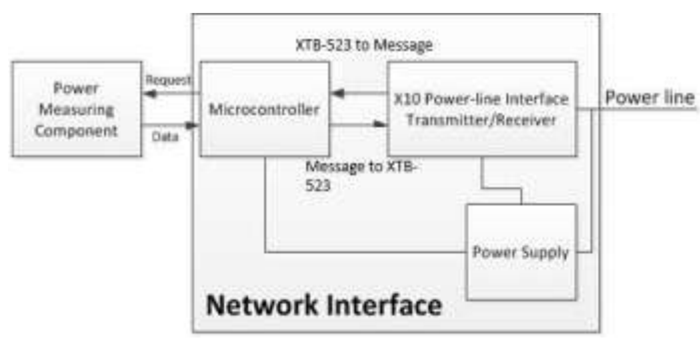

Fig. 4. Power Outlet Monitoring Device Network Interface Block Diagram

Both sides would contain the same parts except that the program of the microcontroller on the server side would be different in the sense that the microcontroller in the power outlet device would be between the power measuring component and the PLC network component, while on the server side the microcontroller would be between the PLC network component and the interface to the server.

2.3 Web UI - Dashboard

The output controller is accessed entirely from the web interface. Any authenticated user can edit the settings present in the interface. The authentication system is implemented through a simple username, password request. Once authenticated, various menus and settings appear on the interface. From there, it is up to the user to select the preferences that is needed to help monitor power consumption rates. A selection of daily, weekly, monthly and annual power consumption can be chosen by the user.

Fig. 5. Sample Webpage

In the interface, a device will have its own line graph which shows its total wattage use over time. The user has the option to view the data on a monthly, weekly or daily time period. It also possible to view the data in the tabular form, providing greater detail of power consumption: wattage, voltage, ampere, VAR, power factor, and kilowatt hour. The user may also have the option of viewing the information from a specific date.

3. SYSTEM IMPLEMENTATION

The power analyzer module is based on the Cirrus Logic's CS5463. The analyzer is able to compute for Voltages, Amperes, Wattage, Apparent Power, Reactive Power, and Power Factor by monitoring the voltage amplitude and phase across a low-valued current-sensing resistor. Its output is in plain-text CSV format and is sent through a TTL UART compatible port to the Gizduino ATmega-328 every second.

For the power-line interface the XTB-523 is used. Its role is to send data from the Arduino microcontroller through the power-line which is received by another XTB-523 device. The data is then sent to the microcontroller connected to it through the RJ-11 port.
An X10 packet contains a house code (4 bits), unit code (5 bits) and command code (5 bits). The unit and command codes has a fixed last bit therefore having 4 flexible or interchangeable bits. These bits are handled by the Gizduino where the house code, unit code and command code are instead replaced by usable, changeable and meaningful data. This produces a 12 bit packet that can be sent through the power line.

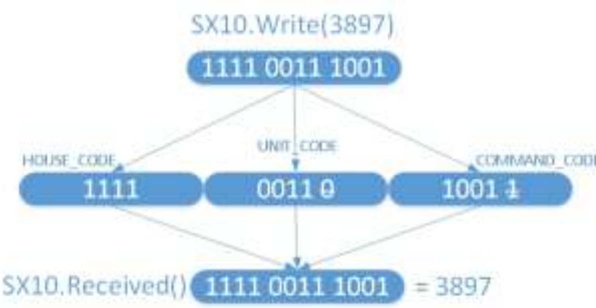

Fig. 6. 12-Bit Transmission Protocol - Flexible Bits

The 12 changeable bits can have a value ranging from 0-4095 ('1111' '1111' '1111'), therefore the XTB-523 can communicate a maximum of 3 decimal digits per packet since the XTB-523 cannot use the thousandth part because it only has a maximum value of 4 (4095), unlike the last 3 digits which can reach the value of 9 each. For this system, a '3' in the thousandth position is used as an identifier to make the receiver know that it is the first part. The second part contains the last 2 digits where 11 is used in the thousandth and hundredth digit to let the receiver know that it is the second half of the whole data that is being transferred.

3.1 Power Consumption Integration

While power consumption can potentially be updated as often as once per second, there is the question of how power consumed over time should be calculated. In tis system, a trapezoidal integration has been chosen, which allows the system to linearly interpolate and effectively calculate the Watt-Second rate.

All of these values get recorded every second as long as the appliance is on. This is to ensure the system does not miss any big changes that may occur during the process of recording the data. The only time it does not record values is when the data is being sent. This is because of the limitation present within the device. Every time data is sent through the power line, WS and time values are reset.

3.2 Accuracy Verification

To verify the accuracy of the power analyzer module, several household light-bulbs were tested, mixing full-length fluorescents, CFLs and LED types.

Table 1. Parser Results

Bulb	Watt	VA	VAR	PF	Volts	mA
3.5W LED (Manu 1)	3.4	6.1	4.7	0.5959	230.96	0.0269
3.5W LED (Manu 2)	2.6	7.4	6.9	0.3742	229.64	0.0328
3.5W LED (Manu 3)	3.0	9.1	8.7	0.3371	232.68	0.0404
3W LED (Manu 4)	3.0	3.0	0.8	0.9406	230.91	0.0140
16W FTL (Manu 5)	16.1	47.0	44.0	0.3456	233.21	0.2011
20W FTL (Manu 6)	29.6	64.5	57.5	0.4583	226.93	0.2847
20W FTL (Manu 7)	29.6	68.9	61.9	0.4358	226.97	0.3030
8W CFL (Manu 3)	6.7	9.5	6.9	0.6993	229.97	0.4278
8W CFL (Manu 5)	8.7	13.9	10.9	0.6144	229.14	0.0614
12W CFL (Manu 5)	10.9	18.7	15.2	0.5858	230.79	0.0814
14W CFL (Manu 5)	14.35	23.9	18.95	0.6130	227.72	0.1057

To verify the consistency and validity of the data in Table 1, mainly the voltage and current of the bulbs, a Volt/Ohm Meter (VOM) was used to measure and compare the recorded data.

Table 2. Volt-Ohm Meter Comparison

Bulb	Volts	mAmps
3.5W LED (Manu 1)	230.6	26.8
3.5W LED (Manu 2)	229.7	32.8
3.5W LED (Manu 3)	232.9	40.8
3W LED (Manu 4)	230.7	14.1
16W FTL (Manu 5)	233.7	20.1
20W FTL (Manu 6)	226.9	28.5
20W FTL (Manu 7)	226.8	30.4
8W CFL (Manu 3)	229.7	43.1
8W CFL (Manu 5)	229.1	61.4
12W CFL (Manu 5)	231.2	81.8
14W CFL (Manu 5)	227.5	10.4

The results from the VOM in comparison with the power analyzer have a small difference, with a maximum error of 0.21% for voltage readings and 0.985% for current (mA) values. This shows that the results between the measuring devices are relatively close to each other and are well within the range of the acceptable error margin. The percentage difference is computed using the following formula:

$$\%\ \text{Diff} = \frac{|\text{VOM} - \text{Analyzer}|}{0.5\ (\text{VOM} + \text{Analyzer})} * 100\% \qquad \text{(Eq. 1)}$$

While the device's accuracy is reliable it is also important to verify if the data sent through the power-lines is successfully received and accurate, several tests were made. Firstly the devices were tested by sending a fixed value of "55555" through the power line every 3 seconds 100 times. This is done to set a base reference for the following tests.

The test yielded a 100% success rate, which is expected since there are no other factors affecting the data that is sent. This proves the reliability of the XTB-523 when it comes to sending data in a controlled environment. Furthermore it is also revealed that sending more than 60 instances causes the XTB-523 to trigger a 'storm shutdown' preventing data from being sent to the power line. The sending process has been changed in order to limit the number of instances it can send within a minute preventing the storm shutdown to trigger.

Further testing included observations on the data based on the length of the medium between devices. An increase in the distance between the devices is done until a variation from the data is seen. Several extension cords connected together from the power outlet is used to implement an increase in length.

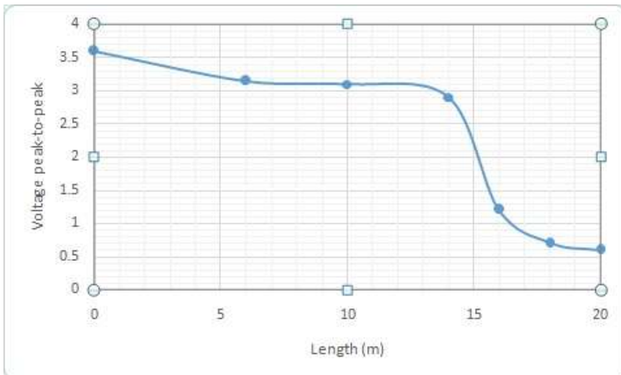

Fig. 7. Attenuation of Signal as Length Increases

The graph shows that there is a 0.4V change in amplitude from zero to 13 meters. A 2V drop occurs when the length increases from 14 to 17 meters. From 17 meters, the amplitude continues to drop but at a lower rate. At the 20 meter mark, the signal amplitude close to the limit where the XTB-523 device is unable to read the X10 signal. The relation of the amplitude to length is, interestingly, not linear.

Noise was also induced into the communications (power) lines by toggling power switches. This includes plugging and unplugging devices during data transmission. Additional signals might come from this process and might affect the data. The effect of plugging in another XTB-523 device during transmission is monitored since there might be a signal burst that is sent while powering up.

Table 3. Toggling Power Switches during Data Transmission

Total Number of Data Sent	100
Total Number of Data Received	99
Total Number of Data Changed	5

99% of the time the data is received, however 4.95% of the data have their values changed. The reason for the dropped data and the change in data is caused by plugging the XTB-523 during data transmission. Every time an XTB-523 is plugged, it sends a HELLO message to the power line. Due to that there is chance that a collision or a change in data might occur. Aside from the XTB-523, devices that sends signals through the power line can affect data transmission. An example of this is if a household has an existing X10 system installed. Other than X10 devices or devices that modify the signals present in the power line, plugging in other devices or toggling power switches does not change or cause any problem to the data being sent.

Other external factors for transmission failures lie in other appliances that possibly insert noise into the power line, as well as absorb the X10 signal present during transmission. Different types of appliances are used to determine some of the factors that may cause interference or absorption. The signal is observed to see changes that are made to it.

Table 4. Effect of Devices with Electric Motors Result

Total Number of Data Sent	100
Total Number of Data Received	100
Total Number of Data Changed	0

Devices with electric motors do not affect the data being sent. Even with multiple blowers plugged in, the data remains unchanged. A 100% success rate is also seen during data transmission while a laptop adapter is plugged. However it was observed that the signal is prone to attenuation because of the capacitors and line filters present in the laptop adapter as seen in Figure 8. Although the attenuation is not enough to cause any problems with data transmission, multiple devices with the same properties may reduce the amplitude to the point where the XTB-523 is unable to read the X10 signal anymore.

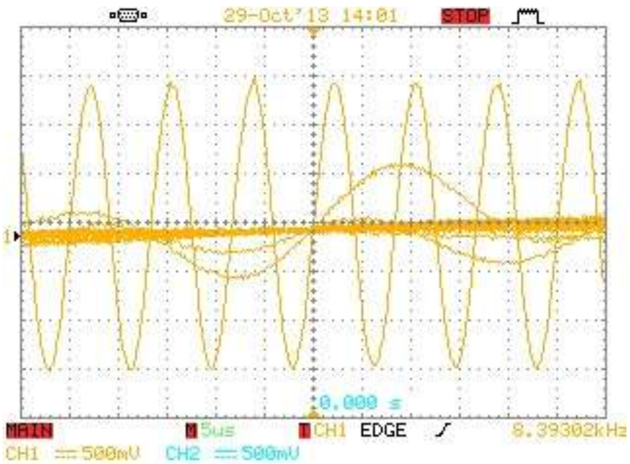

Fig. 8. Effect of Laptop on X10 Signal

Since attenuation was one of the main problems that may occur when transmitting over the power-lines another hindrance to this is the circuit breakers. Residential circuit breakers are known to protect and act as a barrier to household appliances from events such as power surges. The XTB-523's signal amplitude ranges an average of 2Vpp. This test determines if the circuit breaker would treat X10 Signals as power spikes or surges or if the circuit breaker would act as a barrier for the X10 signals.

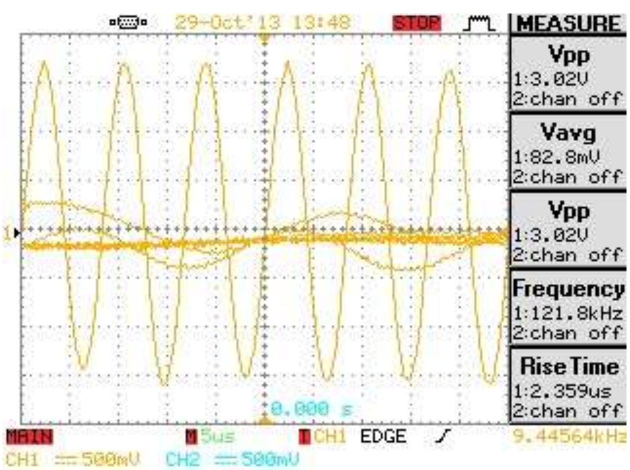

Fig. 9. Signal before Crossing a Circuit Breaker

Before crossing the circuit breaker, the signal has a 3.2 Vpp as seen in Figure 9. After crossing two circuit breakers the signal is attenuated to a value of 400 mVpp. Even though there is a large drop in amplitude, the XTB-523 device might still able to read the signal since it is still within its threshold. This is with the assumption that the XTB-523 device is close to the circuit breaker. Increasing the distance of the XTB-523 device from the circuit breaker may result in a lower success rate in receiving data.

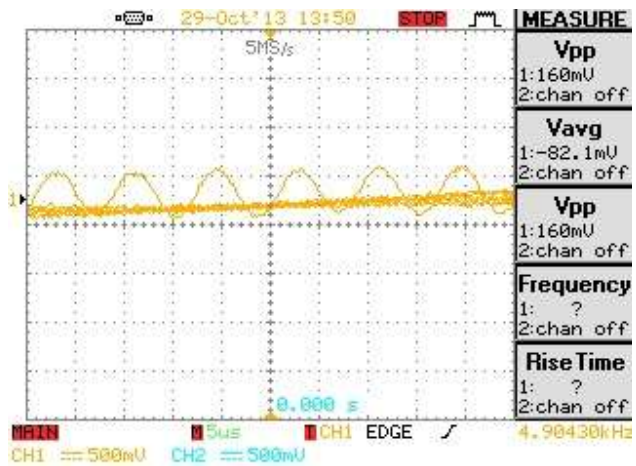

Fig 10. Signal after Crossing a Circuit Breaker

The attenuation is induced by the capacitors present in circuit breakers thus, the more circuit breakers the signal crosses to, the stronger the attenuation in the signal. The attenuation also varies from one circuit breaker to another because of the difference in capacitance involved in each of them.

3.3 Stress Tests

Since some appliances are made to run long hours without stopping the power outlet monitoring device must be able to keep up with the long duration and still be able to perform its task. The behavior of the device must still be consistent and the components should not sustain any damage even if given a heavy load that is sustained for long hours.

In order to test the limits of the monitoring device, its temperature was observed over three days while it was monitoring a water pump and refrigerator, each of which consumes 1300W and 180W, respectively. Results are shown in Table 5.

Table 5. Device Temperature with Load

Time (Minutes)	Temperature (Celsius)	
	180W Load	1300W Load
0	32.01	31.47
2	44.36	55.96
4	47.91	59.29
6	48.34	60.79
8	47.91	62.84
10	49.19	63.16
12	48.12	63.27
14	52.85	62.62
16	48.12	62.73
18	49.41	63.47
20	50.25	61.18

As expected, the temperature with a 1300 watt load is higher compared to the 180 watt load. Despite having a big difference between the two wattages, the temperature increase modest, and well within operating range. The temperature for a given power level was also observed to stabilize at around the 10 minutes of operation. The device continues to send and receive data regardless of the load on the power outlet monitoring device.

3.4 User Interface Survey

Lastly a survey is conducted to understand how helpful the web-interface is in informing the user about their individual and overall appliance energy consumptions. Furthermore it helps identify what the users prefer to see in terms of data shown to them and how easy it is to navigate through the web-interface. The survey contained the following questions

1. Can you easily navigate through the user-interface?
2. Is the initial information shown to you relevant to what you want to see?
3. Is the information detailed in presenting how much energy an appliance consumes?
4. Would the information being shown to you be enough for you to create a power savings plan?

Respondents to the survey vary from household owners (i.e. Parents) and students who live in condominiums/apartments. All 20 respondents had an easy time navigating through the user interface with little to no assistance. The majority of the respondents were happy with what was shown to them, although some wanted to see the computed expense cost of the appliances. With regard to the energy consumption details of each appliance, all respondents were satisfied with the details shown. Lastly, for creating a power savings plan based on information shown by the system all participants responded that this system is helpful.

Table 6. Usability Survey Response

Q#	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1	9	6	0	0	0
2	10	2	1	2	0
3	15	0	0	0	0
4	7	8	0	0	0

4. CONCLUSIONS & FUTURE WORK

A functional hardware device has been successfully developed to measure the power consumption of household appliances using the pre-existing power lines within the household. The device, power outlet monitoring device, uses the XTB-523 to send X10 signals through the power line. The device sends a 120 kHz signal with an amplitude of 3.5Vpp and implements a simple XOR encryption algorithm, which is chosen for its lightweight characteristic, which allows for fast data transmission and provides appropriate security for the type of information that is transmitted. Several tests were done on the device in order to verify its reliability. When in use for a long period of time and while monitoring loads within its design specifications, it is able to operate without any signs of impending failure. The power outlet monitoring device is capable of measuring devices that uses 1 Watt to 1500 Watts or 2200 VA. The system monitors and records the voltage, amperage, wattage, VA, VAR, and PF of the appliance plugged to it. The accuracy of the monitor is within 1% for steady-state consumption.

For future development and commercialization, it is recommended that the components such as the Gizduino ATMega 328, XTB-523 and E-Gizmo Power Analyzer be incorporated into one whole component where they share or use the same components such as the Power Supply and microprocessor as having fewer components the power monitoring device's power factor and energy efficiency. A higher sampling rate is also needed from the Power Analyzer component to improve accuracy of power consumption readings and be able to include sudden power consumption changes.

Based on the usability test, it is recommended that the expense computation of the appliances, both overall and individual, be included in the web-interface. Furthermore it is recommended to conduct a larger scale survey in regards to the system to observe the reactions and effectiveness of it, this will provide further understanding and development of the information given to the household users.

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