A Wireless Energy Custodian Network

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Abstract

This document defines the determined qualities required for the IPFW Senior Design Project: A Wireless Energy Custodian Network. The main goal of this project was to design, build, and test a wireless sensor and actuator network for monitoring the energy usage of AC devices in a home environment. Each node in the network reads the energy usage of an AC device connected to it and wirelessly reports the readings to a central server. The server displays the readings from these nodes through a user interface on a computer in real-time, in such a manner that users can understand their electricity usage patterns and adapt their behavior to reduce energy consumption. Moreover, users are able to remotely control the power On/Off of individual devices via the central server.

1. System Overview

In a world of rising energy costs and dwindling natural resources capable of producing energy, people and businesses are starting to look for better ways to help reduce their increasing electric bills. One way of reducing these costs is to monitor how much power is being consumed in real-time and from that data make informed decisions about how to manage the electrical devices being powered. A system which can give users an idea of how much power is being, has been, and might be consumed will allow them to adjust their habits and lower the costs.

Our project was to design a wireless energy custodian network that will monitor the power usage of alternating current devices/appliances in a home environment. The system consists of two or more “node” modules and a Central Server Module. The nodes record data about the power consumption of the devices/appliances that are connected, and wirelessly transmit that data to the central server for processing. The server displays the readings from these nodes through a user interface in real-time. The goal of this project is to help users better understand how power is consumed by their devices and adapt their behavior to reduce their energy consumption.

Most electronic devices, even if turned off, will continue to draw power from a standard electrical outlet unless the device is manually unplugged. This power is called "*standby power*." Although individual electronic products may not draw enough power while in standby power to be noticed, the average American family has almost forty devices constantly consuming power. The standby power consumption of these devices accounts for almost 10% of household electricity use. Because of this, our design integrates an actuator into each measurement node that will automatically turn on and off the power supply to the AC devices remotely.

The remote on/off control can also be used in other manners to further reduce energy. For example, the air conditioner can be turned on and off remotely based on the inputs from temperature sensor readings and energy usage; the lights can be turned on and off remotely based on the inputs from motion sensor readings and energy usage; the water heater can be turned off before midnight and turned on before sunrise. The design of these appropriate control mechanisms, however, depends on the specific devices and the habits of individual users. Therefore, in our project, we specifically target the standby power to illustrate the feasibility and functionality of the on/off control. Furthermore, this on/off control enhances the wireless network from monitoring only to also including the actuator part, which extends the capability of the whole system and makes our design different from other products on the market.

Figure 1 shows an application of this wireless energy monitoring system in a home scenario, where the measurement nodes are connected to major home appliances in different rooms, and the central server module displays the energy consumption of these appliances on a computer screen.

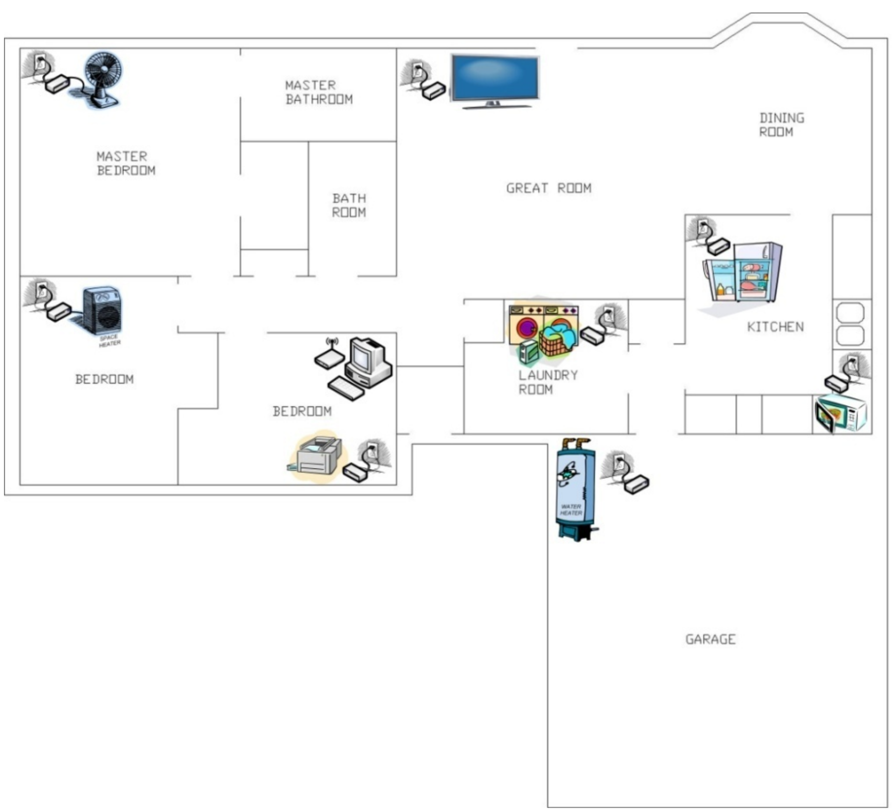

Figure 1: A wireless energy monitoring system at home.

Our group decided to design and implement a system prototype with two measurement nodes and one central server module, where the nodes communicate directly to the server and the server displays the measurement results through the computer. Requirements of the system prototype include:

- The nodes monitor and wirelessly transmit the energy usage of connected AC devices.
- The central server module displays the energy reading in real-time through a graphical user interface while updating once every minute.
- The central server module is able to turn on and off the individual nodes. The on/off control will be tested in the application of standby power reduction.
- The system prototype will be deployed and tested indoors, in a typical home environment in the United States. The communication distance from the measurement nodes to the central server module is within 50 feet.

Some products already on the market which function in a similar manner as the system we designed are the TED 1000 Series and Kill-A-Watt. The TED 1000 series takes the readings from an electrical panel in a home and tracks energy usage of an entire household and can display this information on a computer using the included software [1]. Kill-A-Watt is a device which monitors the amount of energy consumption of a connected appliance by the kilowatt-hour and displays it on an LCD display [2]. Our design is capable of monitoring and *controlling* multiple devices while neither the TED 1000 Series nor Kill-A-Watt can control the appliance.

2. Selection of a Wireless Standard

Our system is targeted for indoor use at a typical American home; therefore a short-distance wireless communication system is more appropriate. Two types of wireless communication standards are suitable for this application: IEEE 802.15.1 (Bluetooth) [3] for medium rate wireless personal area networks (WPAN) and IEEE 802.15.4 (ZigBee) [4] for low rate WPANs.

IEEE 802.15.1 is adapted from Bluetooth, which specifies short-range RF-based connectivity for portable devices. Bluetooth is designed for small and low cost devices with low power consumption. Since Bluetooth is geared towards handling voice, images, and file transfer, it has a data transfer rate on the order of 1Mbps with a relatively complex protocol. The operational range for Bluetooth is only around 10 meters. With amplifier antennas its range can be boosted to 100 meters, but with higher power consumption.

The IEEE 802.15.4 standard specifies the physical layer and medium access control used for the low-data-rate, short-range transmissions that are also well suited for this application and environment. Transfer rates from 20 kbps to 250 kbps will provide sufficient throughput for the amount of data to be wirelessly transmitted. A typical single-family structure will be enclosed within the 100-meter transmission range specified. Additionally, the star network used in our design is one of the two supported network topologies. The central server in our project operates as the PAN coordinator, controlling the two-way communications between the server and each node. Finally, IEEE 802.15.4 standard will allow for expansion to our network as more devices are added to the energy monitoring net.

3. Project Design

Our system prototype has two measurement nodes and a central server module. Each measurement node is plugged into a standard NEMA 15-5 electrical outlet. An AC device is then plugged into the node for power measurement. Each measurement node contains the components necessary to measure the power consumption, wirelessly transmit the information to the central server module, and control the power on/off of the connected device. In order to measure the power consumption, a voltage divider network and low impedance current sense resistor are connected to an energy metering chip. The energy metering chip samples the voltage and current signals, calculates the power consumption, and outputs a pulsed digital signal with a frequency related to the power consumption. The microcontroller then samples the pulsed digital signal from the energy metering chip and converts to a power value. The microcontroller also has the capability of controlling the power delivered to the connected device with a solid-state relay. Several indicator LEDs identify the node's current mode of operation, and a reset button allows the user to restore power to a device that is currently off. The block diagram of the node's components is shown below in Figure 2.

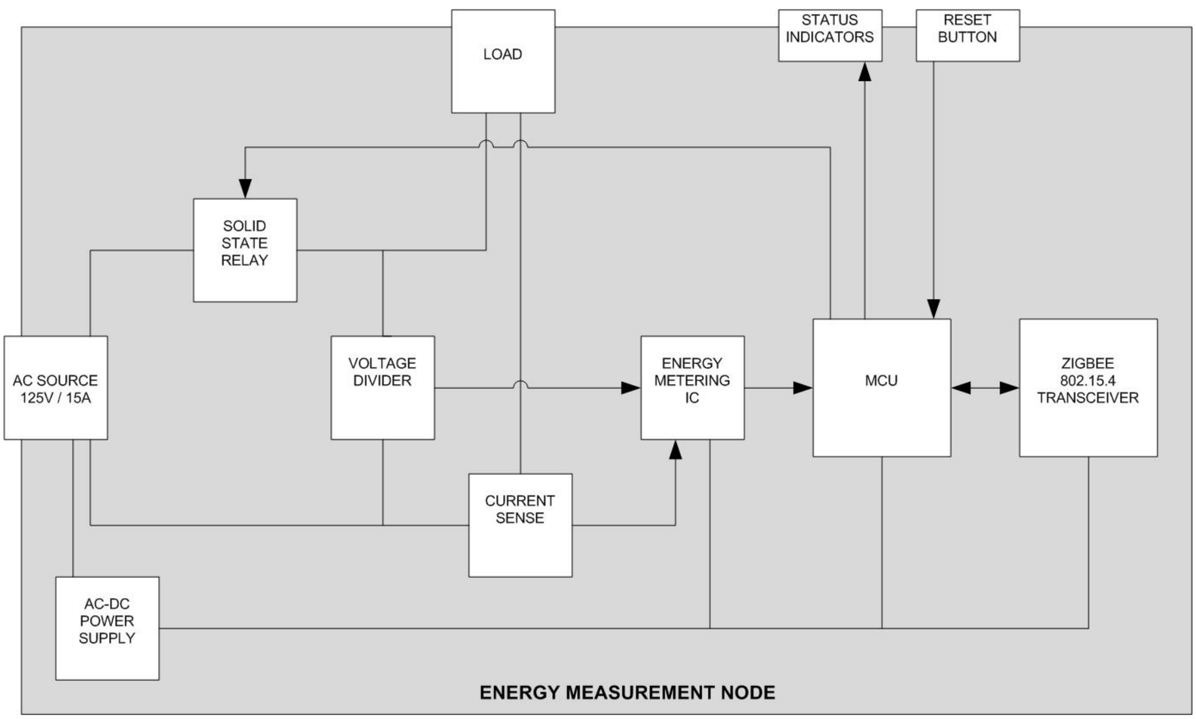

Figure 2: The block diagram of a measurement node.

The central server module (CSM) receives the power measurements from each of the nodes and then forwards the measurements to the computer for display. The measurement data is received through a ZigBee transceiver and passed directly to the computer program through the USB port. The power on/off signals from the computer program are passed to the ZigBee transceiver through the USB port. The components in the central server module are powered through the USB port as well. Figure 3 shows a block diagram of the main components included in the central server module. We used the XBee Explorer Dongle unit [5] from the SparkFun Electronics. This unit has a USB UART interface IC device (FT232RL) that interfaces between the XBee transceiver [6] and the USB port. It is also equipped with a USB port and a dock for the XBee transceiver. The XBee Explorer Dongle cost $24.95 and the XBee transceiver cost $19.00.

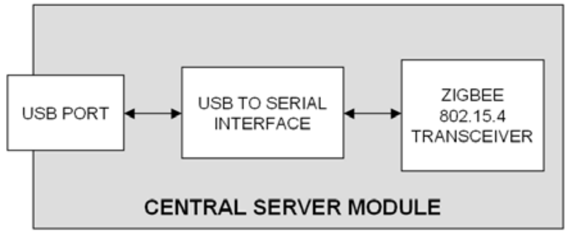

Figure 3: The block diagram of the central server module.

3.1 Measurement Node Hardware

The overall size of the measurement node prototype is 4.7" x 4.7" x 2.4" and the total cost for each measurement node was $112.79. Figure 4 below shows the assembled node with the main components specified.

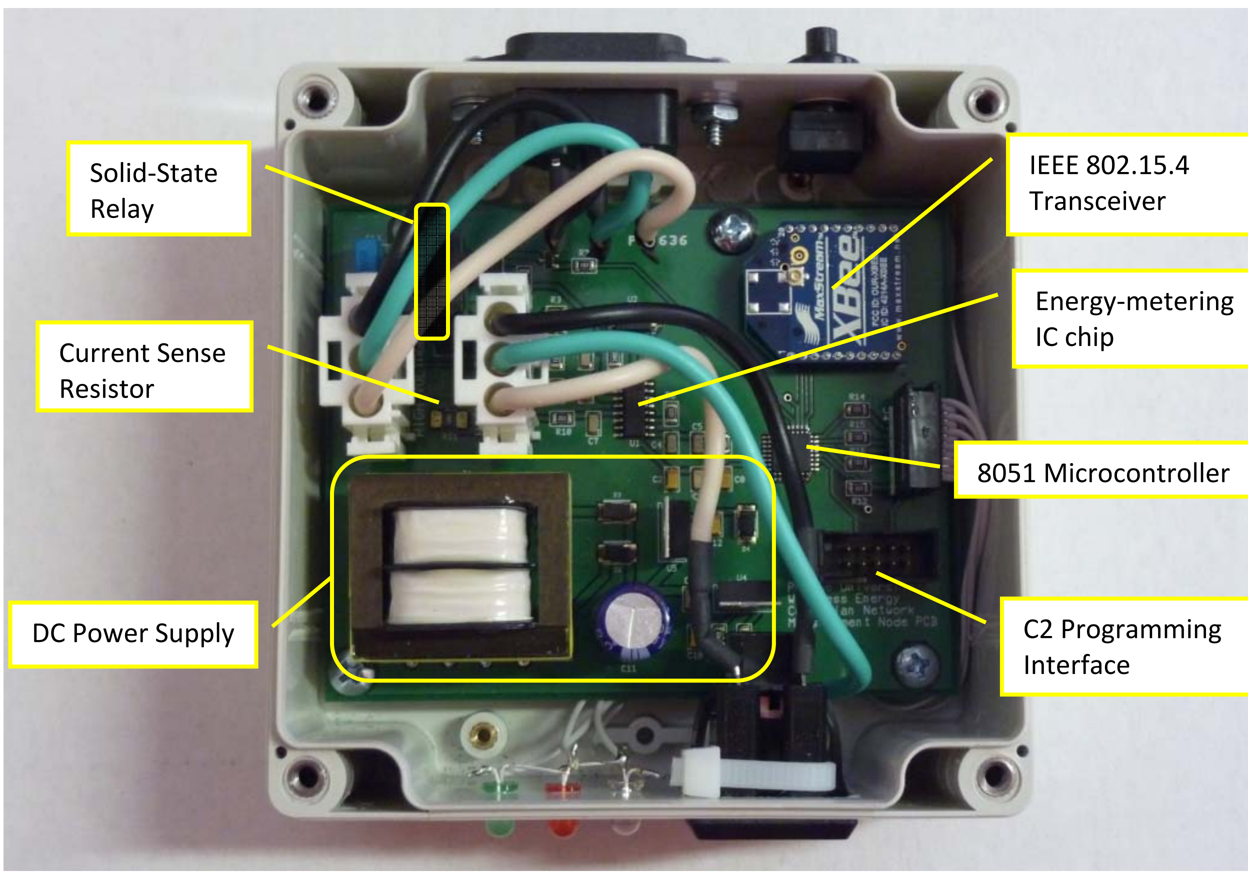

Figure 4: Photograph of the completed measurement node.

3.2 Measurement Node Software

The node software was written and tested using the Keil uVision4 embedded development tool for the 8051 microcontroller [7]. The ANSI C programming language was used to write our code, which was then compiled into a HEX file to program the microcontroller. The main functions of this software include collecting measurements from the energy-metering IC chip, transmitting the measurements to the CSM, receiving control signals from the CSM, and controlling the power supplied to the connected appliance.

3.3 Graphical User Interface (GUI) Software

The GUI software was written for a Windows based personal computer and tested using the Microsoft Visual Studio development suite. The main purpose of the GUI software is to display the power consumption data in real time and control the solid-state relay for each of the nodes. To achieve these goals, the software is organized into two threads: *the transmission thread* and *the user input thread*. The transmission thread will execute once per minute, as that is the rate at which the nodes transmit their data. The transmission thread consists of the reading the wirelessly transmitted data, adding a timestamp, checking the standby power requirements, saving the power measurements to a file, and then updating the graphical display with the latest power measurement. The user input thread allows the software to asynchronously handle input from the user each time the user presses a button on the GUI.

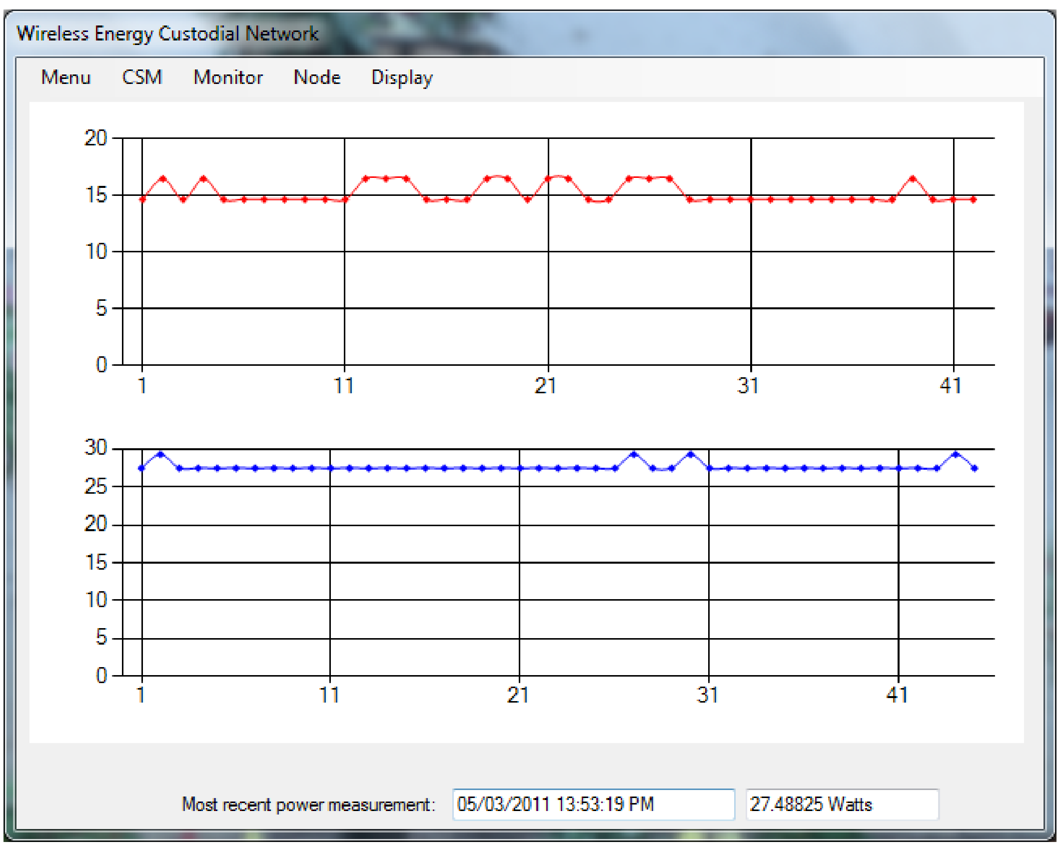

Figure 5: Screenshot of GUI displaying the power consumption for two nodes.

Figure 5 above shows the testing of a space heater with only the fan on (no heat) and an LCD computer monitor. Each of these two devices is~~are~~ plugged into a node and their power consumption are reported to and displayed at the GUI software.

The GUI software also has the capability to calculate the total energy used over a specified period. The user can provide a “start date” and “end date” for the software to calculate the total energy consumed by both nodes. To calculate the energy, the software reads in historical data from the CSV file and multiplies the time duration values by the power usage value. These are summed up and converted from Joules to kilowatt-hours and then displayed to the user. Figure 6 below shows the window displaying the energy consumption for a user-specified time period.

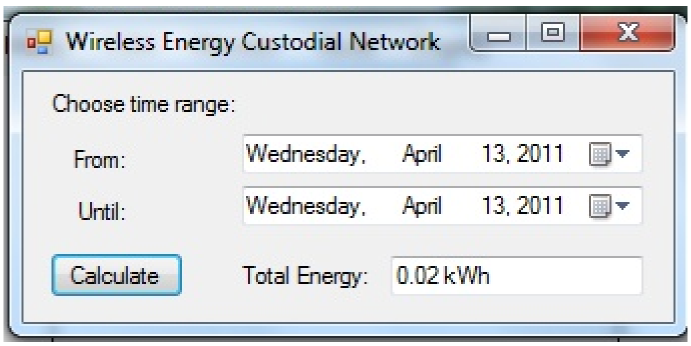

Figure 6: Calculating energy consumption over a time period.

An additional power save feature is included in the GUI software. The purpose behind the power-save feature is to reduce power consumption by devices that go into a “standby” mode. The design and the testing of this power-save feature will be described in detail in Section 4.2.

4. Testing and Evaluation

For our design we tested each of the main components required for proper operation of the nodes and the central server module. This included measuring the power consumption at the node, wirelessly transmitting the information to the CSM, rendering the information on the GUI in real time, and transmitting a control signal back to the node if necessary. For the measurement nodes, the individual components tested included the AC-DC power supply, the solid state relay, the optocoupler, the energy metering IC chip, the IEEE 802.15.4 transceiver. For the CSM, the components tested included an additional IEEE 802.15.4 transceiver and the GUI software. The power supply, solid-state relay, optocoupler, and energy metering IC chip performed as expected during testing and are not discussed in detail here. The wireless transceiver performance and the GUI software evaluation are discussed in further detail below.

4.1 Wireless Signal Testing

Two types of testing were conducted: *range testing* and *impediment testing*. Range testing was testing how far the node and CSM could be placed relative to each other while still receiving a signal which was free of transmission errors. Impediment testing was testing in which the node or the CSM was placed in or around objects which could cause distortion or loss of signal (for example, metallic objects like stoves, refrigerators, etc.) The design requirement was for a range of 50 feet to allow for use inside of a standard home.

The nodes and the CSM were taken to a large three story home with a walk-out basement in Fort Wayne, Indiana. The results of the range testing were as follows in Tables 1-3. For the purposes of this test the result of “Strong” is defined as no noticeable transmission problems while “Weak” is defined transmission reception was sporadic or not at all.

Table 1: Lateral range testing (single floor).

Range (feet)	Impediments	Signal
5	None	Strong
10	None, Interior Brick Wall	Strong
15	None, Interior Brick Wall	Strong
20	None, Interior Brick Wall	Strong
25	None, Interior Brick Wall, Interior Wall	Strong
30	None, Interior Brick Wall, Interior Wall	Strong
35	None, Interior Brick Wall, Interior Wall	Strong
40	None, Interior Walls	Strong
45	None, Interior Walls	Weak

Table 2: Vertical range testing (multiple floors)

Node Floor	CSM Floor	Signal
Upstairs	Ground	Strong
Basement	Ground	Strong
Upstairs	Basement	Strong

Table 3: Impediment testing

Node Level	CSM Level	Comment	Signal
Basement	Ground	Node Inside Washing Machine	Strong
Ground	Ground	Node Inside Oven	Strong
Ground	Ground	Refrigerator Between CSM and Node	Strong

Our testing concluded that the range requirement was satisfied and that no noticeable impairment to the signal occurred when transmitting near or in large metallic objects.

4.2 Standby Power-Save Feature Testing

When the standby power-save feature for a specified node is enabled, the device that is connected to that node is first put to standby mode, and the GUI software gathers the next 10 readings it receives for that node and averages them. The average is multiplied by 120% and set as the threshold for that node. Then the device is set to normal working condition. Once the device has operated for 30 consecutive minutes (i.e., 30 consecutive readings) below the threshold, the GUI software then determines that the device is working under the standby mode and shuts off power to the device via the wireless control signal. Any reading above the threshold resets the count of “below threshold” values.

In order to test the standby power-save feature, we monitored a computer while it was consuming standby power. We first enabled the power-save feature for the computer node, then waited for the 10 samples to be calculated in the threshold calculation phase. After the standby threshold was calculated, we turned on the computer to show usage above the threshold, which should not shut power off to the device. Then, we put the computer back into standby mode, which consumed less than the threshold. After 5 consecutive samples under the threshold were received, power was automatically shut off to the computer. Here we used 5 consecutive samples instead of 30 for the purpose of reducing the testing time and showing a live demo. Figure 7 below shows the GUI after the standby power-save feature was enabled for the computer. As indicated by Figure 7, the computer still consumes around 20 W (about 27% to 33% of its power in normal working condition of 60-75 W) while in standby mode. The GUI software was able to remotely turn off its power automatically after the computer has been in standby mode for a while. Therefore, our designed system is able to help users reduce their energy consumption by reducing the standby power consumption. Once the power of the device is cut off by the CSM, a user can restore the solid-state relay by pressing a push-button at the node, so that the device can be turned on again locally.

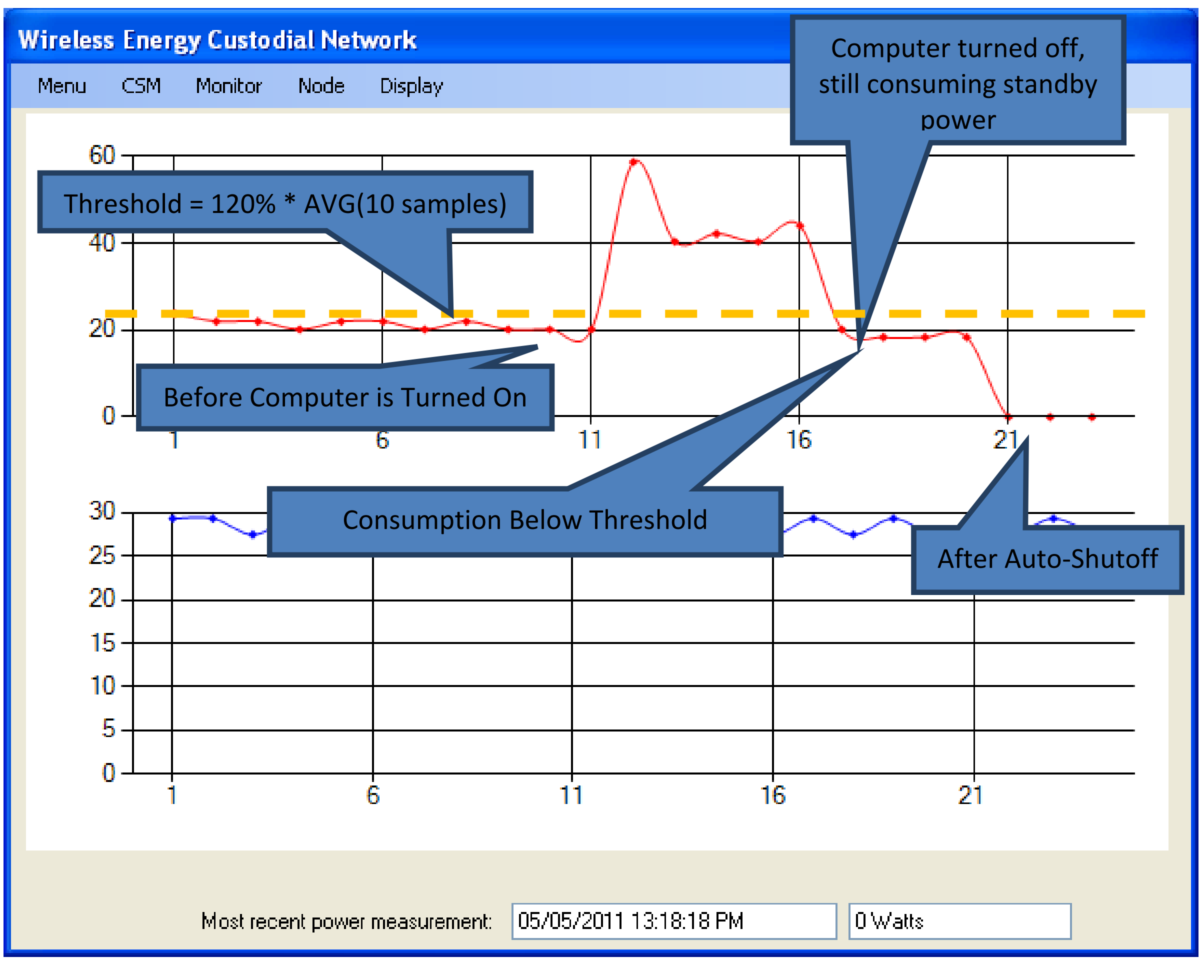

Figure 7: Screenshot of GUI after the computer (top graph) has reached its auto-shutoff point.

5. Conclusion

This paper describes a capstone senior design project that builds a wireless sensor and actuator network for monitoring the energy usage of AC appliances in a home environment. The design of the system prototype including two measurement nodes and a central server module is explained. The system prototype meets the design criteria. Additionally, the implementation and performance analysis of this design project have been completed. The XBee transceiver module selected for this project has a low maximum transmit power of 1mW (0dBm) and a high receiver sensitivity of -92dBm. This resulted in a maximum transmission range of 40 feet between the nodes and the CSM. In the future, a transceiver with a larger transmit power could be tested to improve the network range. Finally, IEEE 802.15.4 standard will allow for expansion to our network as more devices are added to the energy monitoring network.

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