Implementation of a Multi-sensor Wireless System for Reducing Residential Energy Consumption

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Abstract. *This paper deals with the design and implementation of a multi-sensor wireless network system based on XBee for reducing residential energy consumption. Contrary to most commercial products, which measure various physical quantities in one place, the presented solution utilizes distributed measurements using Wireless Sensor Network (WSN). Three nodes or end devices, each equipped with a different sensor, monitor light density, temperature, humidity and presence of people and transmit this information to the coordinator or the controlling unit. The controlling unit, based on the received information, controls the status of electrical appliances such as lamps, fans, and televisions. The experiments show the effectiveness of the system.*

1. Introduction

Energy conservation or reducing energy consumption is one of the biggest challenges of modern society [Beggs 2009], in which the most can be achieved by employing the correct engineering techniques. According to Statistical Yearbook of Electricity [EPE 2014], Brazilian residential buildings dissipate about 27% of total energy, which means reducing energy consumption in residential buildings can result in increased environmental quality and higher savings.

According to [Torresani 2013], many recently built constructions incorporate Modern Building Automation Systems (BAS), which usually incorporate some kind of environmental monitoring system. The key task in most of these monitoring systems is to maintain a comfortable environment with reduced power expenditure.

A WSN is a kind of distributed system to monitor a physical or environmental condition such as sound, movement, temperature, or light and send the information to a central unit. WSNs are recognized as a versatile technology that offers efficient and easy-to-deploy facilities for monitoring applications [Brunelli 2014].

XBee is one of the most popular technologies for communication in WSNs. XBee [Faludi 2011] is a small, modular and cost-effective component that uses radio frequency to exchange data wirelessly in a network; it can be organized as point-to-point, star and mesh topologies and works well with several classes of sensors and controllers. The use of XBee in a WSN gives the freedom to deploy each sensor in a different place and the ability to alter this placement, if needed.

This paper introduces the design and implementation of an automated system for indoor environmental monitoring. The system consists of a central controlling unit and a set of sensor nodes. These nodes continuously measure light, temperature, and humidity and periodically send this information to the controlling unit. The controlling unit, which consists of an XBee transceiver, a microcontroller, a single input and a variety of outputs, depending on the received information and the presence of people in the room, controls the state of electric appliances.

The remainder of the paper is structured as follows. After reviewing some related work in section II, Section III presents the general structure of WSN as well as the functionality of the central controlling unit. In Section IV, some experiments and their corresponding results will be presented and in Section V, some concluding remarks will be discussed.

2. Related Work

The environmental monitoring, using wireless sensor networks, has been an extensive research topic in recent years. Most of the work done in this area focuses on techniques to reduce the cost of the network, while maintaining the overall performance of the sensors.

[Torresani 2013] in his work presents the construction of a multi-sensor wireless network system for monitoring the temperature, humidity and airflow in a building. The system consists of various nodes, each equipped with a different sensor, located on different places and continuously monitoring the ambient temperature, humidity and airflow. The main objective of the work is to derive a correlation between human activities and indoor environmental parameters. Any optimization based on the received data has been left for future work.

[Brunelli 2014] proposes a Wireless Sensor Network system, consisting of 19 sensor nodes for indoor climate monitoring. The sensor nodes, installed on an office floor, continuously measure the vibration, temperature, humidity, light, and carbon dioxide, while various current sensors measure the power load of the system. The work compares the environmental condition and energy load during a long period of measurement and tries to find a balance between inhabitant comfort level and power demands. The data received from sensors serve only for analysis and no feedback or control systems are implemented.

[Seong 2011] studies the development of a switchboard for controlling the status of electrical appliances. The system consists of some control units, each installed on a different room and connected wirelessly using XBee modules. The user, utilizing a remote control, can turn on or off the entire electrical appliance in the building. The paper argues that the system can be of great help to the elderly and in reducing energy waste. Although various experiments assess the performance of the network, there are no experiments to demonstrate the effectiveness of the system on reducing energy waste.

There are two key differences between the project at hand and similar ones. First, each node contains a single sensor that, depending on the structure of the building, can have a different placement; this organization can result in a more accurate reading and reduces the number of needed nodes. Second, the information received by sensor nodes are used to control the status of electric appliances, so the received data here do not serve only for analysis but also for controlling the status of electric appliances.

3. Methods

The present project consists of three major steps: first, defining the network infrastructure on which the system communication is based; second, selecting the appropriate sensors and implementing the sensor nodes; and finally, developing the main controlling unit. All the steps will be described as follows.

3.1. Network Architecture

The proposed wireless network system uses XBee Series 2 modules, which support the ZigBee protocol.

ZigBee [Nugroho 2014] is a standard communication protocol for low-power, wireless networking. It uses the IEEE 802.15.4 standard and adds additional routing and networking functionalities. The XBee Series 2 modems offer some advanced features, like data encryption and power saving mode and, in addition, they can be configured to work with star or mesh topologies.

In the work at hand, due to the small number of sensor nodes, the star topology (Figure 1) has been adopted, in which all the communications are via the coordinator and there are no direct communications between the end devices.

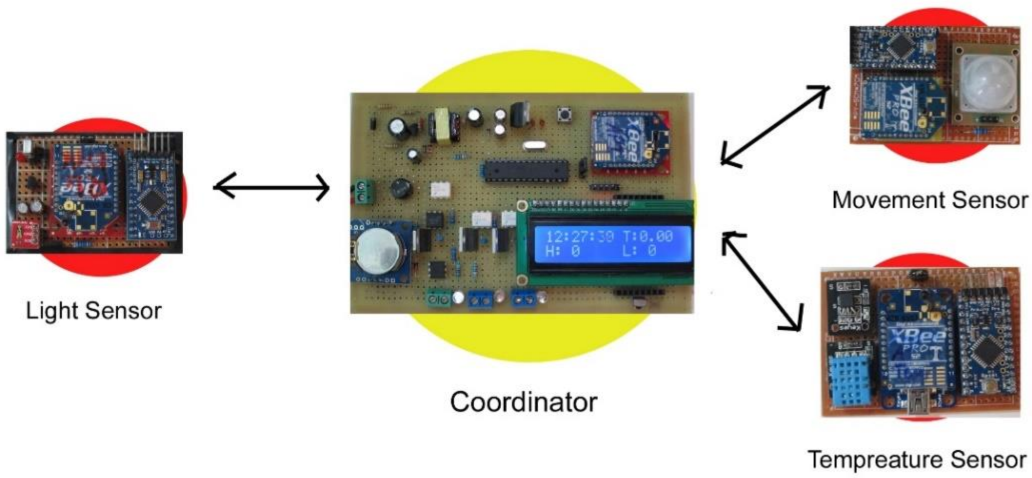

Figure 1. The star topology

The proposed topology consists of two types of node: sensor nodes and a coordinator node. The sensor nodes, each equipped with a different sensor, have the role to monitor some physical quantities, such as temperature, humidity, light, movements, and transmit the information to the coordinator. The coordinator node tries to establish connection with the sensor nodes and controls the status of electric appliances based on the received information.

The coordinator modem is configured to transmit the received data in “API Mode”, in which the microcontroller, connected to the modem via serial port, receives the data in a packet called a frame. Each frame (Figure 2) consists of various bytes of information and has a well-defined structure.

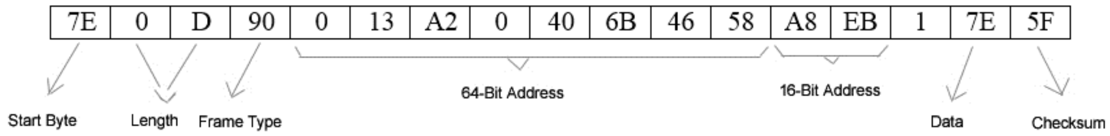

Figure 2. A sample data frame in API mode

Once the connection between the end device and the coordinator is established, the coordinator, based on the address of the sender, available on the frame, discovers the type of data, and this data will be saved on the microcontroller memory.

3.2. Sensor Nodes Features

All the node sensors (Figure 3) have a similar structure: they are all battery powered and contain an XBee PRO S2 transceiver, an Atmega328 microcontroller, a 3.3 and a 5v voltage regulator and a dedicated sensor. Each will be described next.

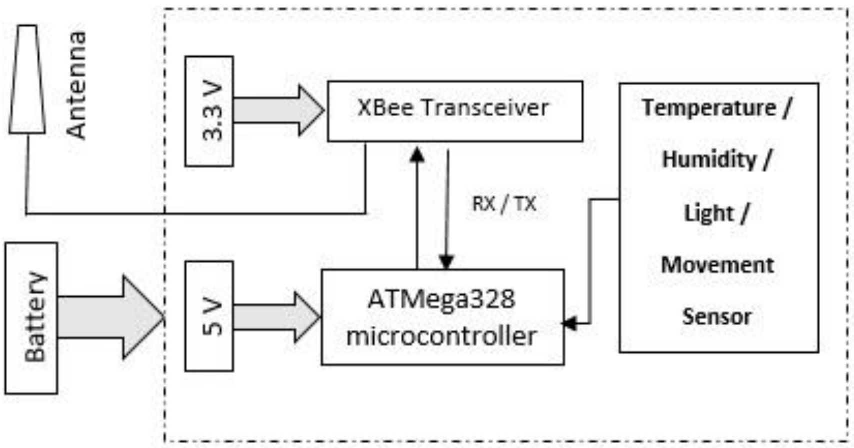

Figure 3. Block Diagram of a sensor node.

3.2.1. XBee PRO S2 Transceivers

These transceivers, supporting the ZigBee protocol, have a maximum data rate of 250kbps and, with the help of an internal antenna, can have a maximum range of 400m indoors and 1600m outdoors. These modules, by simply using a serial port, can communicate with various kinds of microcontrollers and processors.

3.2.2. ATmega328 microcontroller

ATmega328 is a small-factor, low-power and relatively cheap microcontroller that can be used in sensor nodes to control the functioning of the sensors, as well as the transferring of the data. Although some analog sensors can communicate directly with XBee modules, the sensors used in this project, for proper functioning, need an external microcontroller. The ATmega328 can be loaded with the Arduino optoboot, allowing the use of Arduino code without using the actual Arduino board.

3.2.3. Sensors

A sensor is an electronic component which can sense or detect some characteristics in the real world and provide a corresponding output, generally an electrical or optical signal. In this project, four different sensors (Figure 4) have been used.

a) TEMT600 Ambient Light Sensor | b) PIR D203S Pyroelectric Infrared Radial Sensor | c) RHT03 Digital Relative Humidity Sensor | d) DS18B20 1-wire Digital Thermometer

Figure 4. The sensors used in the project.

The TEMT6000 (Figure 4.a) is a silicon NPN analog phototransistor. This sensor is sensitive to the visible spectrum and is adapted to human eye responsivity. It has a linear response to the incoming light, which means the greater the incoming light, the higher the output voltage. The sensor has a wide angle of half sensitivity, $\phi = \pm 60°$, and is widely used in computers, cell phones, cameras and dashboards to control the backlight dimming.

The PIRD203S (Figure 4.b) is a pyroelectric infrared sensor (PIR); these sensors function based on the fact that any object with a temperature above zero emits heat energy in the form of radiation and that the polarization of pyroelectric material changes with temperature. Therefore, by detecting the infrared radiations from objects, the voltage output of the sensor varies, and movements can be detected. This sensor has applications in security systems, burglar alarms and light switch controls.

The RHT03 (Figure 4.c) is a humidity and temperature sensor with a single wire digital interface. The sensor is pre-calibrated and has an 8-bit output resolution. It has an accuracy of +-2 percentage for relative humidity and +-0.5 degrees Celsius for temperature. This sensor is relatively cheap but has a lower response time to changes in temperature, compared to other temperature sensors like DS18B20.

The DS18B20 (Figure 4.d) is a one-wire digital temperature sensor which has a 12-bit output resolution and can operate in temperatures ranging from -55° Celsius to +125° Celsius with an accuracy of ±0.5° Celsius. DS18B20 has applications in industrial systems and consumer products and can be incorporated in thermometers.

3.3. The main controlling unit Hardware/Software infrastructure

The main controlling unit or the coordinator (Figure 5), which is powered directly from the electric network, receives the information from the sensor nodes and contains all the needed software and circuitry to control the state of electric appliances.

Upon turning on the system, the coordinator tries to detect and communicate with the node sensors. The user, using the remote control, can control the system outputs manually or set them in automatic mode. In automatic mode, the output in each instant depends on the received information from the sensors; depending on the ambient light, the dimming output will vary, and depending on the temperature and humidity, the speed of the fan or state of the air conditioner will change. Moreover, if the PIR sensor does not detect any movements in a predefined time, e.g. 10 minutes, the lamps and TV will be switched off.

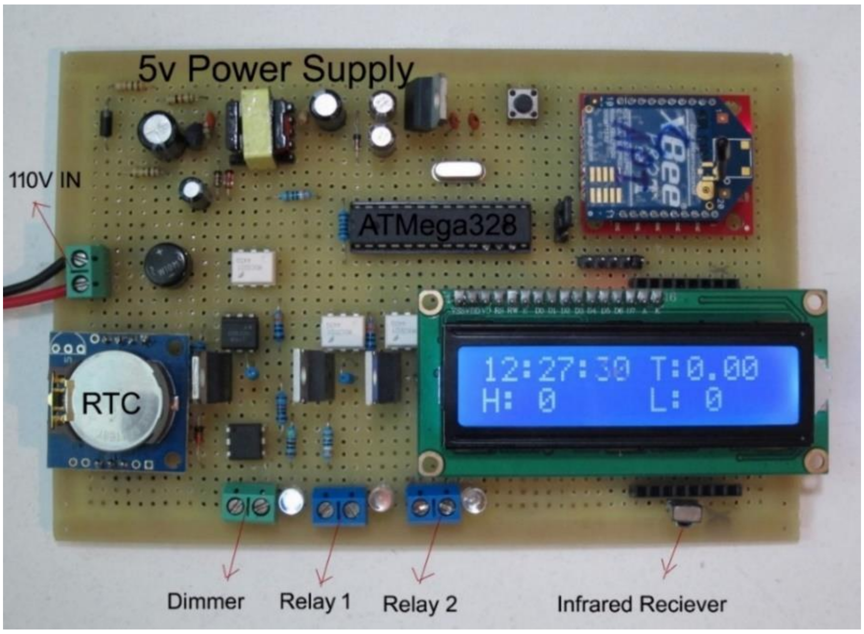

Figure 5. The prototype of the main controlling unit

The software, embedded on the microprocessor, can be divided into three major parts (Figure 6): the main function (Figure 6.a), which contains an infinite loop of instructions; the function to receive and decode data from XBee transceiver (Figure 6.b); and the functions to control the outputs of the system, e.g. the brightness of the lamps (Figure 6.c). The function that controls the ambient temperature is very similar to the one for adjusting the light density, which is not presented here.

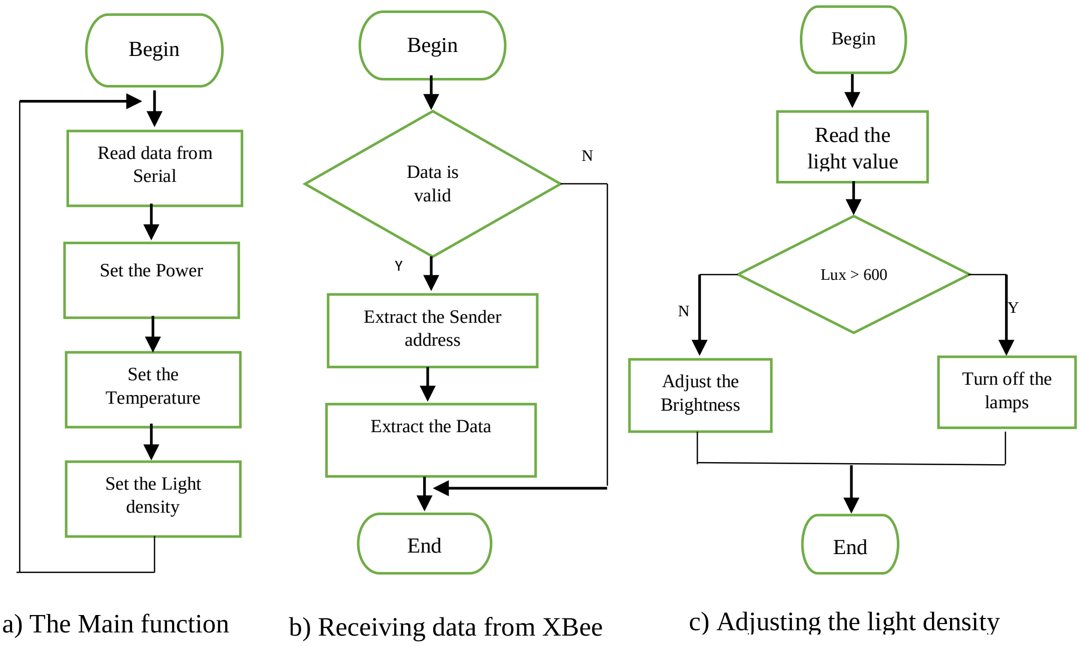

Figure 6. The flowchart of some functions in embedded software

In order to control the brightness of the lamps and the speed of the fans and change the state of electrical appliances, the controlling unit contains some additional circuitry: a zero-cross detector, three solid-state relays and an infrared transceiver. The zero-cross detector in combination with the solid-state relay makes up the dimmer circuit, which will be described in the following.

3.3.1. Dimmer circuit

Dimmers are a kind of electronic device, which by changing the output voltage waveform, can lower the brightness of the lamps and decrease the speed of the fans or a motor, etc. The presented dimmer circuit consists of a zero-cross detector (Figure 7.a) and a solid-state relay (Figure 7.b).

The zero-cross detector is a circuit which can detect the zero-crossing points of a signal. The core element of the circuit is an opto-coupler, connected directly to the energy source or through a full-wave rectifier, and generates a pulse whenever it detects the passing signal through the x-axis or 0 volts. The microcontroller uses the zero-crossing signal as a reference point for the dimmer circuit.

The solid-state relay consists of an opto-coupler and a Triac and has the same functions as an electromechanical relay which, in combination with the zero-cross detector, makes up the dimmer circuit. As a dimmer, it receives from the microcontroller a signal, the dimming value, which defines the dimming level on the load, and as a relay, depending on the command it receives from the microcontroller, it passes or blocks the electricity on the load.

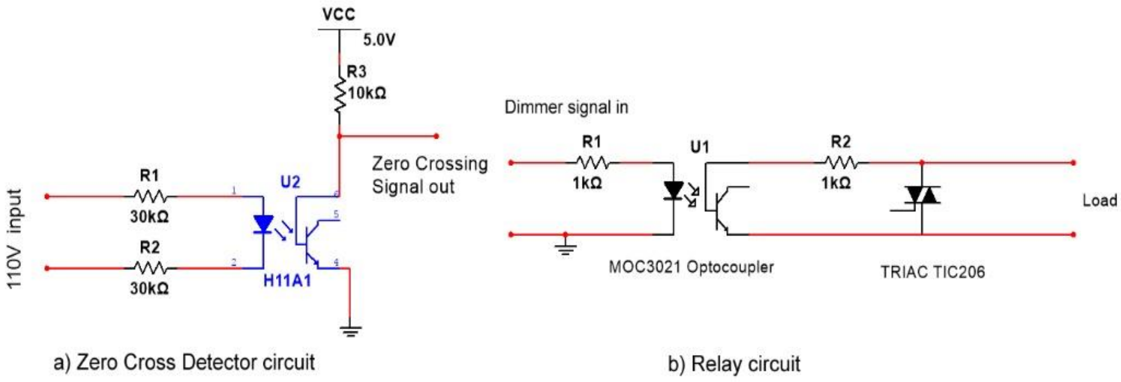

Figure 7. The zero-cross detector and solid-state relay

4. Experimental Results

Some preliminary experiments were carried out to verify the operation of the system, as well as to measure the performance of the sensor nodes. A simple WSN, consisting of three sensor nodes and the controlling unit, was deployed in a residential building in the city of Manaus.

The first experiment was conducted to verify the correct behavior of sensor nodes, consisting of three sensors, all placed outdoors to monitor light, temperature, and humidity and to report these data to the controlling unit. The data received by the controlling unit, sent from the sensor nodes every 30 seconds, are plotted in (Figure 8) and (Figure 9). Such data refer to a 12-hour record collected on a sunny day in April 2015.

Figure 8. Data received from the Temperature / Humidity sensor

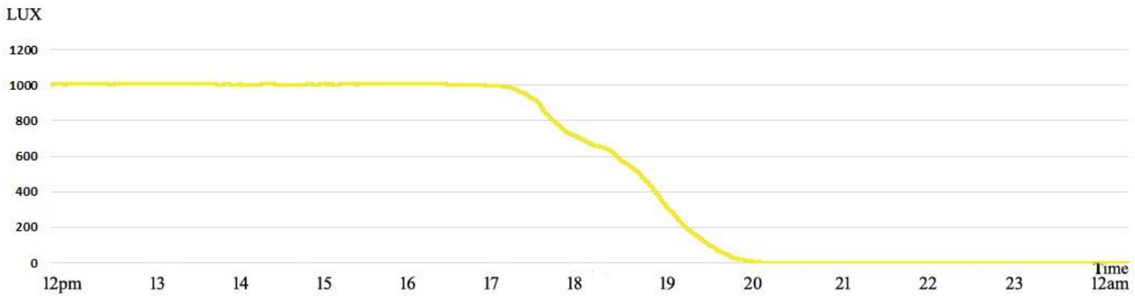

Figure 9. Data received from the Light sensor

The collected data show the variation of the temperature, relative humidity and light density during the test. The temperature varies from a minimum of 29.9^{o} C to a maximum of 34.7^{o} C, and the humidity varies from 50% to 73.9%. Although the temperature at night decreases, the readings show an increase in relative humidity, so for thermal comfort, the combination of two readings should be considered. The readings from the light sensor, when exposed to direct sunlight, do not vary significantly, so the proposed light sensor is adequate for situations where internal sources of light do not alter the readings.

The second experiment, which is aimed to verify the effectiveness of the system for reducing the energy consumption, consists of the same set of sensor nodes, plus a set of electrical current sensors. The current sensors are responsible for measuring the power output of the system. The controlling unit, depending on the light density and temperature of the room, adjusts the fan speed and the dimming level of the lamp. For comparison, a set of identical lamps and fans are connected directly to the power grid, which have constant power consumption. During the test, the power consumption of each peripheral is sampled for each 30s.The collected data from the light sensor and the power consumption of each lamp, changing with the light density, are shown in (Figure 10) and the ambient temperature with the power consumption of each fan are shown in (Figure 11). Such data refer to a 12-hour record collected in the same period in the first experiment.

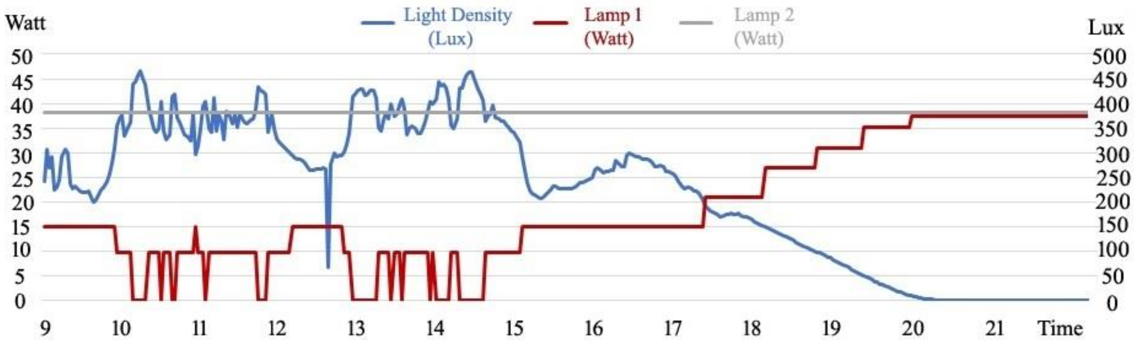

Figure 10. The light density and power consumption of the lamps

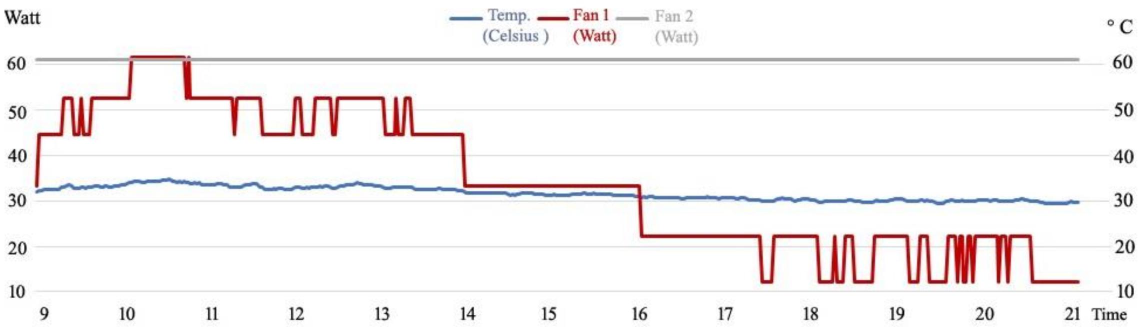

Figure 11.The temperature and power consumption of the fans

As these graphs show, the lamp and the fan, connected directly to the power grid, have constant power consumption, whereas the power consumption of the lamp and the fan connected to the controlling board varies: as the ambient light increases, the lamp output decreases, and the fan speed depends directly on the ambient temperature. So the controlling board automatically controls the power output, which can result in reducing the overall power consumption.

5. Conclusion

In this paper, a prototype based on WSN for monitoring some physical quantities and controlling the status of electric appliances has been presented. The system can be used to reduce the energy consumption in a residential building. Although there are several different sensors available on the market, the experimental results confirm that the chosen sensors are suitable for the intended application. Some experiments were carried out to verify the correct behavior of the controlling unit and sensor nodes; the controlling unit, based on the received data from the sensor nodes, can alter the state of electric appliances. The experiments show that the system is best suited to work in buildings with outdoor lighting and in places which have many variations in temperature or humidity.

More complex scenarios, such as those for buildings with various rooms, may need more sensor nodes and could benefit from utilizing the mesh topology. In addition, the system can be connected to the Internet and be controlled via a web browser or software, so the user can remotely control the state of electric appliances and monitor the overall power consumption of the building. These changes can improve the overall performance of the system and will be left as future work.

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