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WSN-Based Smart Sensors for Power Management in Intelligent Buildings

K.RAJA[1], M.SHOBANA[2,] M.Premalatha[3]
[1,2]PG Scholar, Gnanamani College of Technology, Namakkal, India

Abstract—The design and development of a smart monitoring and controlling system for household electrical appliances in real time has been reported in this paper. The system principally monitors electrical parameters of household appliances such as voltage and current and subsequently calculates the power consumed. The novelty of this system is the implementation of the controlling mechanism of appliances in different ways. The developed system is a low-cost and flexible in operation and thus can save Electricity expense of the consumers. The prototype has been extensively tested in real-life situations and experimental results are very encouraging.

I. INTRODUCTION

It is foreseen that service and personal care wireless mechatronic systems will become more and more ubiquitous at home in the near future and will be very useful in assistive healthcare particularly for the elderly and disabled people. Wireless mechatronic systems consist of numerous spatially distributed sensors with limited data collection and processing capability to monitor the environmental situation. Wireless sensor networks (WSNs) have become increasingly important because of their ability to monitor and manage situational information for various intelligent services. Due to those advantages, WSNs has been applied in many fields, such as the military, industry, environmental monitoring, and healthcare.

The WSNs are increasingly being used in the home for energy controlling services. Regular household appliances are monitored and controlled by WSNs installed in the home. New technologies include cutting-edge advancements in information technology, sensors, metering, transmission, distribution, and electricity storage technology, as well as providing new information and flexibility to both consumers and providers of electricity. The ZigBee Alliance, wireless communication platform is presently examining Japan's new smart home wireless system implication by having a new initiative with Japan's Government that will evaluate use of the forthcoming ZigBee, Internet Protocol (IP) specification, and the IEEE 802.15.4g standard to help Japan to create smart homes that improve energy management and efficiency. It is expected that 65 million households will equip with smart meters by 2015 in the United States, and it is a realistic estimate of the size of the home energy management market. There are several proposals to interconnect various domestic appliances by wireless networks to monitor and control such as provided. But the prototypes are verified using test bed scenarios. Also, smart meter systems like have been designed to specific usages particularly related to geographical usages and are limited to specific places. Different information and communication technologies integrating with smart meter devices have been proposed and tested at different flats in a residential area for optimal power utilization, but individual controlling of the devices are limited to specific houses. There has been design and developments of smart meters predicting the usage of power consumption. However, a low-cost, flexible, and robust system to continuously monitor and control based on consumer requirements is at the early stages of development. In this study, we have designedand implemented a ZigBee-based intelligent home energy management and control service. We used the ZigBee (the IEEE 802.15.4 standard) technology for networking and communication, because it has low-power and low-cost characteristics, which enable it to be widely used in home and building environments. The paper focuses on human-friendly technical solutions for monitoring and easy control of household appliances. The inhabitant's comfort will be increased and better assistance can be provided. This paper emphasizes the realization of monitoring and controlling of electrical appliances in many ways.

The developed system has the following distinct features.

1) Use of Traic with opto-isolated driver for controlling electrical appliances: Household appliances are controlled either remotely or automatically with the help of fabricated smart sensing unit consisting of triac –BT138.

2) No microprocessor/microcontroller: The design of smart sensing unit does not require a processing unit at the sensing end.

3) Flexibility in controlling the appliances: Depending on the user requirements, appliances can be monitored and controlled in different ways.

Section III-B discusses about the various options of controlling the devices. The rest of this paper is organized as follows: Section II discusses the related work and investigation of WSN's constraints for home energy management systems; Section III provides detailed implementation of the developed system; Section IV presents the experimental results and Section V has concluded and discussed about the future work.

II. RELATED WORK

In this section, we briefly discuss the existing works about smart home systems based on the wireless communication technology. Han et al. proposed a Home Energy Management System (HEMS) using the ZigBee technology to reduce the standby power. The suggested system consists of an automatic standby power cutoff outlet, a ZigBee hub and a server. The power outlet with a ZigBee module cuts off the ac power when the energy consumption of the device connected to the power outlet is below a fixed value. The central hub collects information from the power channels and controls these power channels through the ZigBee module. The central hub sends the present state information to a server and then a user can monitor or control the present energy usage using the HEMS user interface. This facility may create some uneasiness for the users. For example, if the users may want low intensity of light, for some situation but the system will cut the power off leading to darkness. Gill etal. projected a ZigBee-based home automation system. This system consists of a home network unit and a gateway. The core part of the development is the interoperability of different networks in the home environment. Less importance is given to the home automation. Pan et al. recommended a WSN-based intelligent light control system for indoor environments, such as a home for a reduction in energy consumption.

In this paper, wireless sensors are responsible for measuring current illuminations and the lights are controlled by applying the model of user's actions and profiles. Song et al. suggested a home monitoring system using hybrid sensor networks. The basic concept of this paper is a roaming sensor that moves the appropriate location and participates in the network when the network is disconnected. Suh and Ko proposed an intelligent home control system based on a wireless sensor/actuator network with a link quality indicator based routing protocol to enhance network reliability. Nguyen et al. have proposed a sensing system for home-based rehabilitation based on optical linear encoder (OLE); however, it is limited to motion capture and arm-function evaluation for home based monitoring. Huiyong et al. examined the integration of WSN with service robot for smart home monitoring system. The above mentioned home monitoring and controlling systemshave limitations with respect to true home automation such as:

1) energy consumption control mechanism is limited to only certain devices like light illuminations, whereas several household appliances can be controlled;
2) energy control is based on fixed threshold power consumption, which may not be applicable to different consumers;
3) controlling the home appliances through network management functions, in practice inhabitant requirements may vary according to their behavior but not with network characteristics. Not a single system has taken into consideration of variable tariff of electricity, which is consumed throughout day and night.

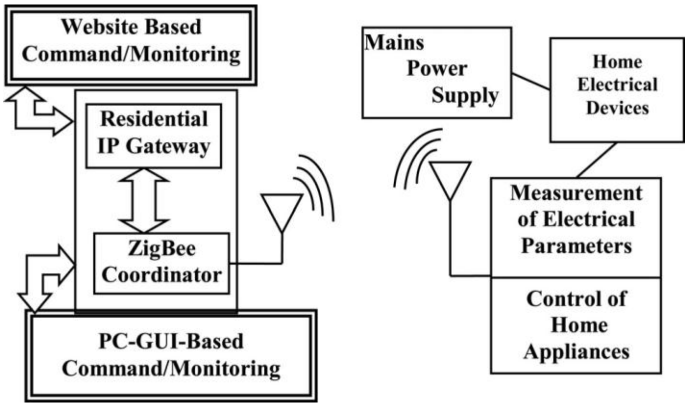

Fig. 1. Functional block diagram of the system.

In this paper, a low-cost, flexible, and real-time smart power management system, which can easily integrate and operate with the home monitoring systems such as presented.

III. SYSTEM DESCRIPTION

The system has been designed for measurement of electrical parameters of household appliances. Important functions to the system are the ease of modeling, setup, and use. From the consumer point of view, electrical power consumption of various appliances in a house along with supply voltage and current is the key parameter. Fig. 1 shows the functional description of the developed system to monitor electrical parameters and control appliances based on the consumer requirements. The measurement of electrical parameters of home appliances is done by interfacing with fabricated sensing modules. The details of the design and development of the sensing modules are provided in the following sections. The output signals from the sensors are integrated and connected to XBee module for transmitting electrical parameters data wirelessly. The XBee modules are interfaced with various sensing devices and inter-connected is in the form of mesh topology to have reliable data reception at a centralized ZigBee coordinator. The maximum distance between the adjacent ZigBee nodes is less than 10 m, and through hopping technique of the mesh topology, reliable sensor fusion data has been performed.The ZigBee coordinator has been connected through the USB cable of the host computer, which stores the data into a database of computer system. The collected sensor fusion data have been sent to an internet residential gateway for remote monitoring and controlling the home environment. By analyzing the power from the system, energy consumption can be controlled. An electricity tariff plan has been set up to run various appliances at peak and off-peak tariff rates. The appliances are controlled either automatically or manually (local/remotely). The smart power metering circuit is connectedto mains 240 V/50 Hz supply. Fig. 3(a) and (b) shows the fabricated smart sensing measurement system.

A. Measurement of Electrical Parameters

Fig. 2 shows different appliances connected to the developed smart sensing system.

1) **Voltage Measurement:**

The voltage transformer used in our paper is the 44 127 voltage step-down transformer manufactured by MYRRA [23]. The striking features include two bobbins compartments including self-extinguishing plastics and very light weight (100 g). The step-down voltage transformer is used to convert input supply of 230–240 V to 10 VRMS ac signal. The secondary voltage is rectified and passed through the filter capacitor to get a dc voltage. The available dc voltage is reduced by a potential divider to bring it within the measured level of 3.3 V of the ZigBee. This output signal is then fed to analog input channel of ZigBee end device. The acquired voltage signal is directly proportional to the input supply voltage. A voltage regulator is connected to the rectified output of voltage transformer to obtain the precise voltage supply of 3.3 V for the operation of ZigBee and operational amplifier. The scaling of the signal is obtained from the input versus output voltage graph as shown in Fig. 4. The actual voltage is thus obtained as follows:

$$\text{Vact} = \text{m1} \times \text{Vmeasured voltage} \quad (1)$$

Where m1 is the scaling factor obtained, Vact is the actual voltage, and Vmeasured voltage is the measured sensing voltage.

2) Current Measurement:

For sensing current, we used ASM010 current transformer manufactured by Talema [24].

The main features of this sensor include fully encapsulated PCB mounting and compact size. The circuit design layout for current measurement is shown in Fig. 3(a). In this current sensor, the voltage is measured across the burden resistor of 50 Ω. The necessary filtering and amplification is required to bring the voltage with the necessary measurement level of ZigBee. The scaling factors for current measurement for two different ranges of currents are shown in Fig. 5. Two different current transformers are used for two different ranges: 0–1 A and 1–10 A, respectively.

Fig. 3. (a)Overall schematic of voltage, current sensing circuit integrated with ZigBee module.

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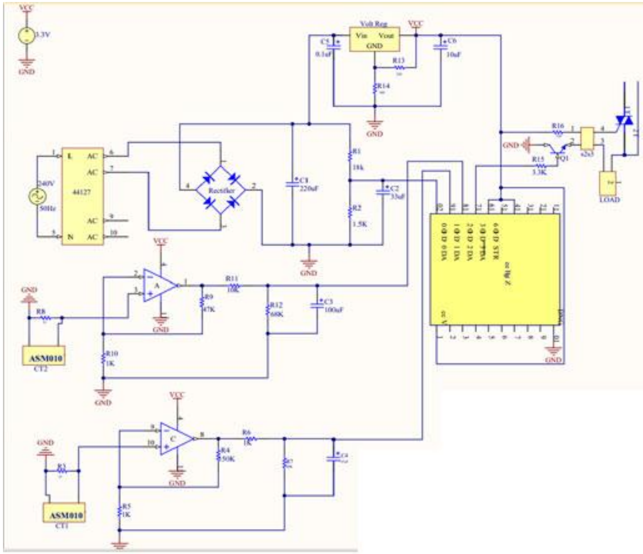
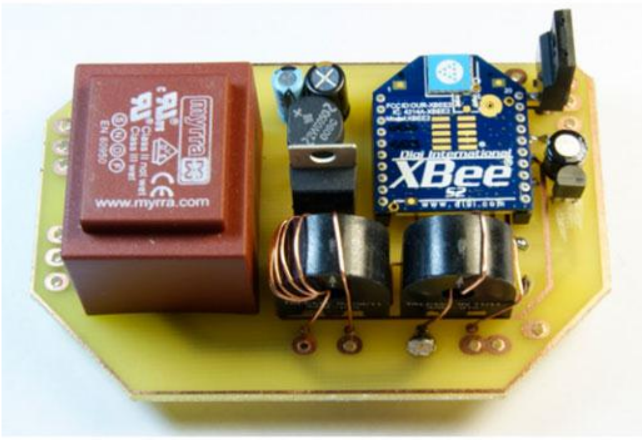


(a)



(b)

(b) Designed and developed prototype—electrical appliances1 power monitoring and control.

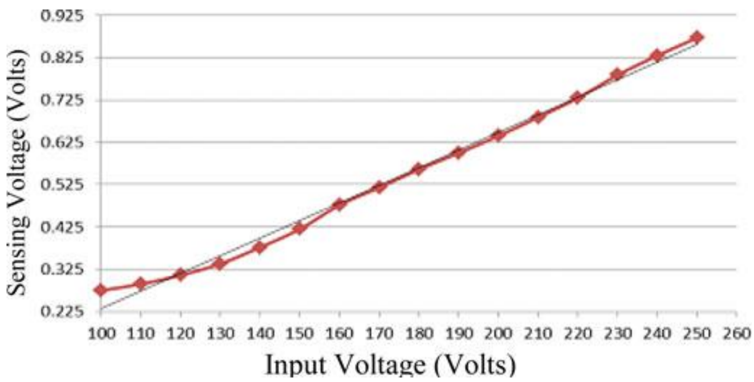


Fig. 4. Scaling factor (m1) of voltage signal

The actual current is thus obtained from (2). The line wire is connected to the load, which is passing through the current transformer. With the use of current transformer, the electrical isolation is achieved which is important in many applications as well as for the safety of the electronic circuit.

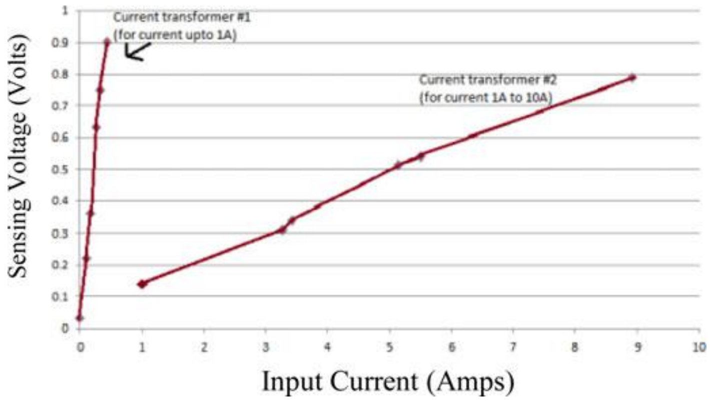


Fig. 5. Scaling factor (m2) of current signal.

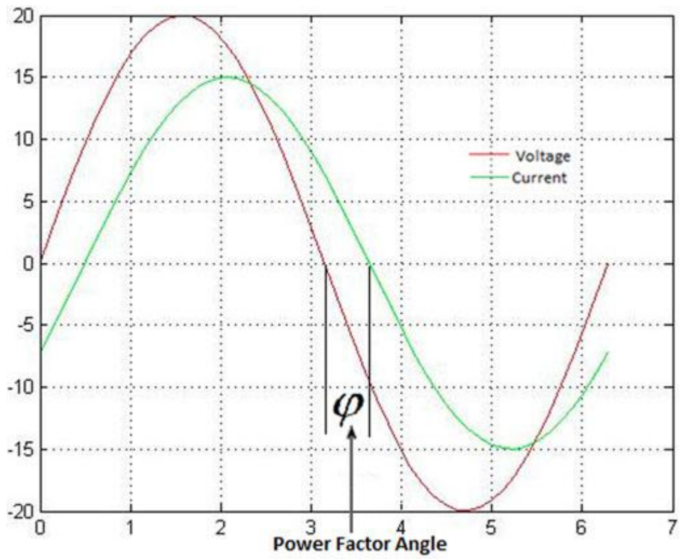


Fig. 6. Representation of power factor

$$Iact = m2 \times Vmeasured\ voltage\ for\ current \quad (2)$$

Where m2 is the scaling factor obtained from Fig. 5, different values ofm2 to be used for different current transformers. Iact is the actual current; Vmeasured voltage for current is the measured sensing voltage for current.

The developed system includes two current transformers; one is used for the measurements of loads up to 100Wand the other current transformer is used for the measurements of loads from 100 to 2000 W. The reason of providing two transformers is to provide two load outlets at the same sensing node. The number of turns is increased up to five turns to improve the resolution of the low current signal. Both outputs from the current transformers are fed to the analog input channels of ZigBee.

3) Power Measurement:

In order to calculate power of a single-phase ac circuit, the product of root mean square (RMS) voltage and RMS current must be multiplied by the power factor as given in (3). Power factor is the cosine of the phase angle of voltage and current waveforms as shown in the Fig. 6 for an ideal situation

$$Pact = Vrms \times Irms \times Pf \quad (3)$$

where Pact is the actual power, Vrms and Irms are the RMS values of voltage and current, respectively, and Pf is the power factor. The output signal of the current transformer completely depends on the nature of the connected appliances whether the connected load is purely resistive, capacitive, or inductive. In most of the domestic appliances, the output waveforms are not pure sinusoidal as shown in the following graphs Fig. 7(a)–(d) for different loading conditions. From the graphs, it is inferred that zero-crossing determination is difficult to measure for some of the appliances and elimination of noise is not trivial. Moreover, it is not important for this application to measure power with zero error. Hence, in our paper, instead of measuring power factor, we have introduced correction factor to normalize the received power with respect to the actual power based on the scaling factors of the voltage and current measured. The power consumed by the appliances is calculated in the computer system after receiving voltage outputs from corresponding current and voltage sensors by the following equation:

$$Pcal = Vact \times Iact \times Cf \qquad (4)$$

where Pcal is the calculated power; Vact the output voltage as given in (1); Iact the current value as given in (2); and Cf is the correction factor.

The term correction factor is introduced to calculate power accurately by the system. The correction factor is the ratio of actual power to the measured power. Correction factor is required for the power measurement for some loads. This correction factor can be obtained by plotting graph for calculated power against the actual power. Thus, the power is calculated in computer using CSharp programming after receiving voltage outputs from corresponding current and voltage sensors.
The prototype has been tested and results achieved for many household electrical appliances are shown in the following section. Table I shows the percentage error for all measured parameters with the corresponding references. It is seen that the maximum error is less than 5% for the domestic appliances. From the low percentage error of power, it has been decided that power can be calculated without considering power factor.

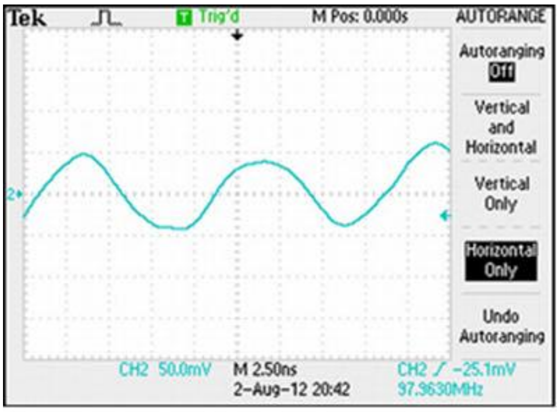
B. Control of Home Appliances

The current paper is novel in terms of other reported literature due to its control features.

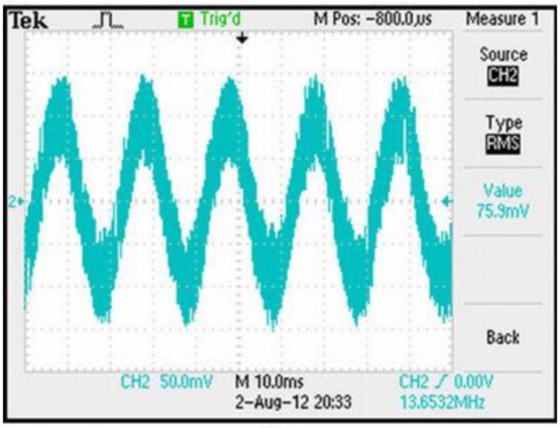
1) Smart Power Metering System integrated With Traic:
For switching on/off of the electrical appliances, we have used a triac-BT138 [14]. This enables the consumer for flexibility in controlling the devices: The users (inhabitants) have the options of switching the device on/off in three different ways.

2) Automatic control:
Based on the electricity tariff conditions, the appliance can be regulated with the help of smart software. This enables the user to have more cost saving by auto switch off the appliances during the electricity peak hours. The electricity tariff is procured from the website of the electricity supply company and is updated at regular intervals.

Fig. 7. Output waveform of current transformer for different appliances



(a)



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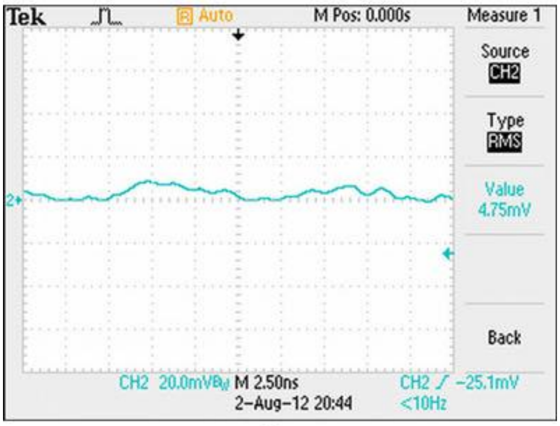

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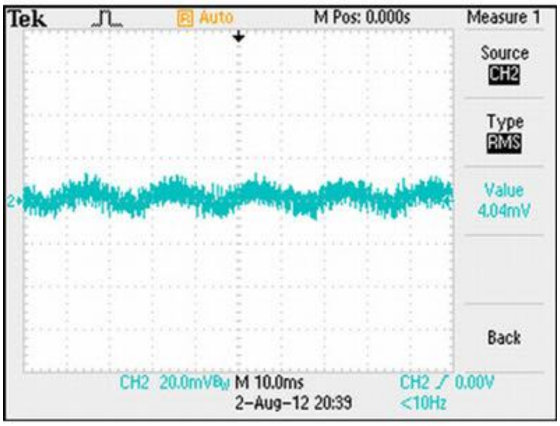

(d)

(a) Output waveform of current transformer for 100 W electric bulb, (b) output waveform of current transformer for 800Wroom heater, (c) output waveform of current transformer for 60 W electric bulb, and (d) output waveform of current transformer for audio device.

TABLE 1. PERCENTAGE ERROR OF RECEIVED VOLTAGE, CURRENT, AND MEASURED POWER

Appliance	Ref. Load (W)	V ref (V)	I. Ref (amps)	Mea. Vol (V)	%Error-Voltage	Mea. Cur (amps)	%Error-Current	Cal. Power (W)	%Error-Power
Bulb	25	229	0.11	229	0	0.11	0.00	25.19	0.76
Bulb	39	229	0.16	230	0.22	0.17	4.25	38.1	4.61
Bulb	59	229	0.26	229	0	0.27	3.85	61.83	4.80
Bulb	73	229	0.32	229	0	0.32	0.00	73.28	0.38
Bulb	98	228	0.43	229	0.44	0.42	2.33	96.18	1.86
Heater	401	226	1.73	225	0.44	1.82	5.20	409.5	2.12
Heater	755	223	3.41	222	0.44	3.45	5.86	781.91	3.56
Heater	1155	224	5.15	223	0.44	5.16	6.43	1145.23	0.85
Toaster	811	226	3.49	226	0	3.56	1.17	808.97	0.25
Toaster	665	234	2.90	235	0.43	2.73	2.01	658.72	0.94
Heater	733	236	3.11	237	0.42	2.91	0.19	703.1	4.08
Heater	1217	235	5.19	236	0.43	5.05	2.70	1192	2.05
Heater	1902	233	8.17	234	0.43	7.83	4.16	1869	1.74
Kettle	1995	233	8.72	233	0	8.18	6.20	1917.2	3.90

2) Manual control:
An on/off switch is provided to directly intervene with the device. This feature enables the user to have more flexibility by having manual control on the appliance usage without following automatic control. Also, with the help of the software developed for monitoring and controlling user interface, user can control the device for its appropriate use. This feature has the higher priority to bypass the automatic control.

3) Remote control:
The smart power monitoring and controlling software system has the feature of interacting with the appliances remotely through internet (website). This enables user to have flexible control mechanism remotely through a secured internet web connection. This sometimes is a huge help to the user who has the habit of keeping the appliances ON while away from house. The user can monitor the condition of all appliances and do the needful. Thus, the user has the flexibility in controlling the electrical appliances through the developed prototype.

C. Residential IP Gateway:

Transmission Over IP In order to transmit real-time sensed data over the internet from the collected computer system, the ZigBee packet information is to be transformed to the Internet Protocol Version 6(IPv6). The key element in the data transformation from Zig-Bee packet is the address translation. This was implemented at
the application gateway, a program for determining the source or destination address of a packet that encapsulates a ZigBee packets' payload.The corresponding application gateway program performs
the address transformation mechanism for ZigBee to address non-ZigBee nodes. ZigBee is based upon the IEEE 802.14.5 protocol, which uses a 64-bit address for each node on a personal area network (PAN) and 16 bits to identify the PAN ID. IPv6 uses 128 bits to address a node on the network, of which 48 bits represent the network, 16 bits represent the local network (PAN ID), and 64 bits represent the host id (sensor node). Therefore, the node address for the IEEE 802.15.4 can be

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placed in an IPv6 address, and the PAN ID can be used to identify the Fig. 8. Address transformation from ZigBee sensing unit to Internet packet. ZigBee network in an IPv6 address. Fig. 8 shows the address transformation of ZigBee and IPv6 packet. The software used on the internet gateway to transmit data globally is the Linux-Open WRT [25]. This is basically router firmware software providing the networking architecture to participate in many types of internetworks. In order to remotely monitor and control the household appliances the residential internet gateway uses the Openwrt software to link to the internetworking protocol. These networks are embedded into internet routers and gateways for broadcasting data globally. The sensed data is forwarded through a tunneling and tapping (tun/tap) device driver software. The tun/tap acts as virtual network device software for bridging and routing functionalities (layer 2 and layer 3) of Internet Protocol (IPv6).

Fig. 8. Address transformation from ZigBee sensing unit to Internet packet.

D. Storage of Data

The ZigBee packets produced at the gateway encapsulate sample data to be sent to windows based internet server. An application on the server receives packets on an arbitrary port and stores the relevant information in the background of MySQL database in the computer. The database table store information such as source address, time, source channel, and sense data. Rows are added to this table for each packet received. This allows samples to be sorted by time, sensor node, and sensor channel. In the present system, programs for address, packet transformations, and data transmission are written using "C" programming language, programs for packet reception and data storage are written using "C#," and Web interface is developed using PHP Script and Java Scripts.

IV. EXPERIMENTAL RESULTS

The prototype is in operation in a trial home with various electrical appliances regularly used by an inhabitant. The following appliances were tested: room heaters, microwave, oven, toasters, water kettle, fridge, television, audio device, battery chargers, and water pump. In total, ten different electrical appliances were used in the experimental setup; however, any electrical appliance whose power consumption is less than 2000Wcan be used in developed system. The sampling rate for the fabricated sensing modules was setup with 50 Hz, so that electrical appliance usages within (less than 10 s) interval of time will be recorded correctly. By Fig. 9 Smart power monitoring and control system at the residence. Fig. 10 Graphical user interface of smart power monitoring and control system at the local residence monitoring consumption of power of the appliances, data are collected by a smart coordinator, which saves all data in the system for processing as well as for future use. The parameters will be entered in the data coordinator in software from appliances include voltage, current, and power. These parameters will be stored in a database and analyzed. Collected data will be displayed on the computer through graphic user interface (GUI) window so that appropriate action can be taken from the GUI.

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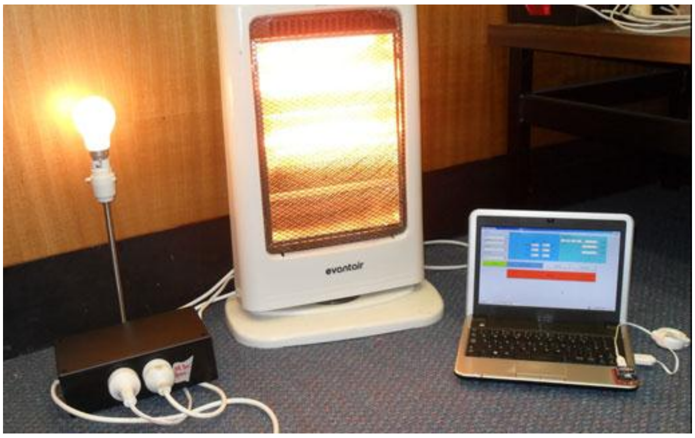


Fig. 9 shows the smart power monitoring and control system at a house where the system is on trial.

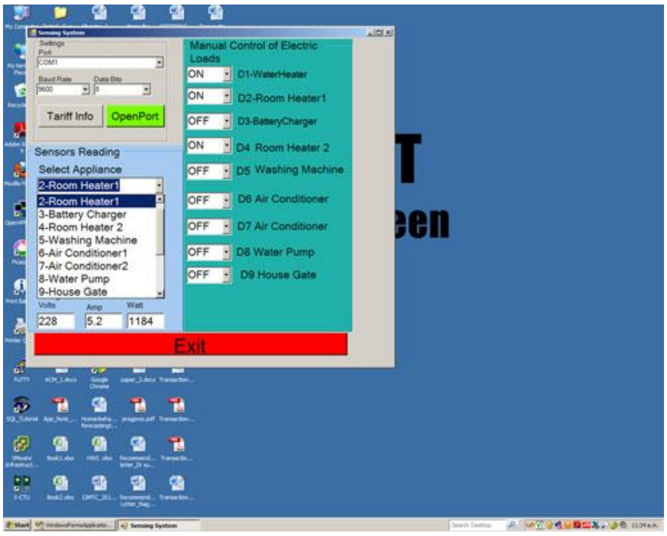
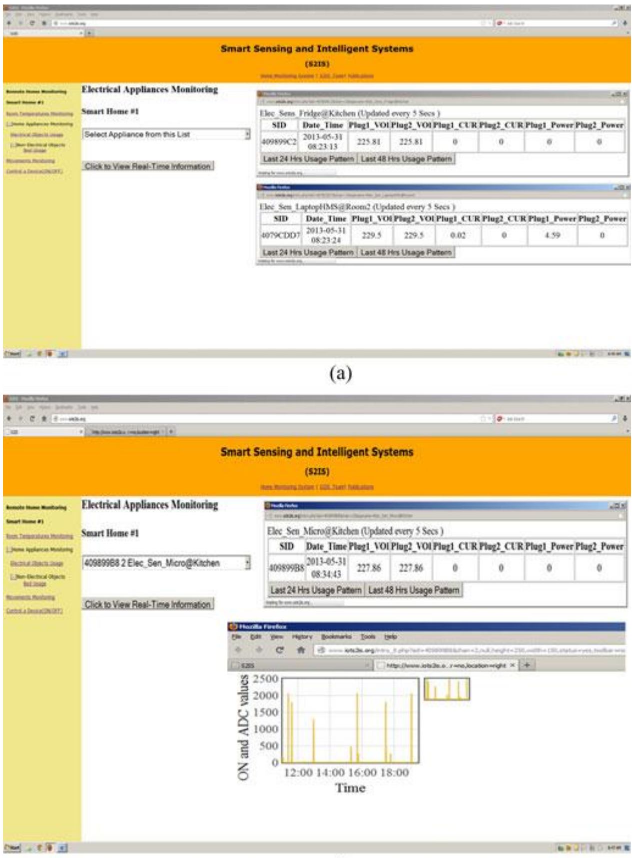


Fig. 10 shows the front end of the smart software system at the local residence.

The processed voltage, current, and power values are displayed on the graphical user interface running on a computer. The processed data are accurate and user friendly. The sensing system in the sensor node measures the parameters (voltage and current). The raw data (i.e., converted ADC values) are transmitted to the coordinator. The computer then collects the data from the coordinator and processes them. The computer then applies the necessary formulas to get the actual voltage, current, and power consumption of the electrical appliances. The voltage and current readings are processed using C sharp programming.



(a)

(b)

Fig. 11. (a) Website (www.iots2is.org) displaying the real-time information (power consumption of appliances fridge and laptop). (b) Website (www.iots2is.org) displaying real-time information (power consumption of microwave appliance) and last 24 h usage pattern.

The developed system has software recovery strategies such as exception-handling, auto restart, and alert text mechanism for sensors failure. The exception handling procedure can handle errors such as no sensor data reception and high range values of analog-to-digital-converted values and computational errors resulted during the normalization of voltage and current sense data values. Depending on the inhabitant usages, appliances connected by smart sensing units are controlled either by automation based on the tariff conditions or by the inhabitant locally using GUI and remotely using the website. The tariff conditions refer to the situation wherein unimportant electrical appliances will be automatically switched off by the system during high price of the electricity. Fig. 11(a) shows the real time usage pattern of a fridge on a particular day. Fig. 11(b) depicts the regular usage pattern of an electrical appliance without tariff control. The system is easy to use as these devices can be controlled remotely using the secured website as shown in Fig. 12. Thus, the regular household electrical appliances along with smart sensing have been internetworked through internetworking technology by integrating ZigBee with IPv6 for better remote management of household appliances.

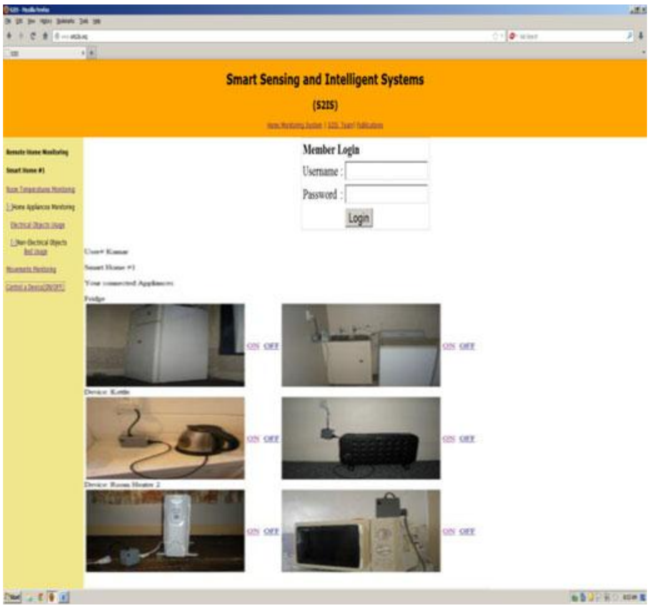


Fig. 12 Secured webpage for controlling appliances remotely after successful authorized login.

V. CONCLUSION AND FUTURE WORK

A smart power monitoring and control system has been designed and developed toward the implementation of an intelligent building. The developed system effectively monitors and controls the electrical appliance usages at an elderly home. Thus, the real-time monitoring of the electrical appliances can be viewed through a website. The system can be extended for monitoring the whole intelligent building. We aim to determine the areas of daily peak hours of electricity usage levels and come with a solution by which we can lower the consumption and enhance better utilization of already limited resources during peak hours. The sensor networks are programmed with various user interfaces suitable for users of varying ability and for expert users such that the system can be maintained easily and interacted with very simply. This study also aims to assess consumer's response toward perceptions of smart grid technologies, their advantages and disadvantages, possible concerns, and overall perceived utility. The developed system is robust and flexible in operation. For the last three months, the system was able to perform the remote monitoring and control of appliances effectively. Local and remote user interfaces are easy to handle by a novice consumer and are efficient in handling the operations. In future, the system will be integrated with co-systems like smart home inhabitant behavior recognitions systems to determine the wellness of the inhabitant in terms of energy consumption.

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