Development of Wi-Fi Based Home Energy Monitoring System for Green Internet of Things

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***Abstract*—Green Internet of things (IoT) has been heralded as the “next big thing” waiting to be realized in energy-efficient ubiquitous computing. Green IoT revolves around increased machine-to-machine communications and encompasses energy-efficient wireless embedded sensors and actuators that assist in monitoring and controlling home appliances. Energy efficiency in home applications can be achieved by better monitoring of the specific energy consumption by the appliances. There are many wireless standards that can be adopted for the design of such embedded devices in IoT. These communication technologies cater to different requirements and are classified as the short-range and long-range ones. To select the best communication method, this paper surveys various IoT communication technologies and discusses the advantages and disadvantages to develop an energy monitoring system. An IoT device based on the Wi-Fi technology system is developed and tested for usage in the home energy monitoring environment. The performance of this system is then evaluated by the measurement of power consumption metrics. In the efficient deep-sleep mode, the system saves up to 0.3 W per cycle with an average power dissipation of less than 0.1 W/s.**

***Index Terms*— Energy efficiency, energy monitoring, Internet of things.**

1. Introduction

Internet of things (IoT) is expected to have an astounding impact on our daily activity and become an inherent part of areas, such as healthcare, transportation, utilities management, control, retail, and electricity[1],[2]. By 2020, approximately 26 billion objects will be linked together in the Internet[3]. Devices in IoT, ranging from smart phones to embedded sensors, fulfill three important requirements of computation, organization, and communications[4]. These three requirements are essential to allow devices to be connected in IoT[5].

For traditional wireless networks that are deployed, a master gateway, a router or an access-point (AP) commonly interfaces the wireless devices with the Internet over a single hop configuration[6]. Wireless local area networks (WLANs) constitute a vital part of the IoT, as many IoT devices make use of IEEE 802.11 technology for connecting[7]. Similarly, IoT devices may also use IEEE 802.15.4 as their communication standards, but they would still require a master gateway for establishing the connection to other devices over the Internet. A single user is expected to own a multitude of IoT devices, which will be used for various sensing and actuating purposes.

Energy monitoring is one key application in IoT with the potential to affect daily life. The increasing adoption of smart meters has led to more innovative solutions in the smart grid industry particularly in the telemetric technology. Smart meters are used to monitor the aggregate total consumption of a house-hold, usually a few times in a day[8]. However, obtaining energy consumption data in real time will significantly enable the development of innovative solutions for the current problems. A key aspect of any energy monitoring system is flexibility. In order to increase the value of the energy monitoring data, the system should be able to monitor and collect data up to the appliance level, and with a larger sensing frequency.

For a home energy monitoring system, a gateway or AP will reside and provide services for devices to connect to the Internet. Such a concept can be extended for the case of WSNs where a large deployment may take place and scalability issues in terms of delay and collision may arise[9]. Currently, many solutions are available in the market for energy monitoring purposes. OpenEnergyMonitor.com introduces a system that has the capability to monitor various parameters of an electrical system such as alternating current (AC) power, temperature, and humidity with hopes of extending the measurements to include other air measurements like moisture. Few companies of Taiwan such as Billion and Insergy have product lines for energy monitoring as well.

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In this paper, we present the development of a Wi-Fi based home energy monitoring prototype to monitor and measure the energy usage in a home setup. The data collected then can be used by users to understand their home energy consumption patterns. To achieve this, we first survey various IoT wireless technologies to select the ideal communication protocol based on our requirements. After selecting Wi-Fi as the technology of choice, we survey IoT Wi-Fi modules available in the market to compare the price and ease of embedded development. Section 2 presents the related works and Section 3 discusses design and implementation. Section 4 presents results and discussion followed by the conclusion.

2. Related Works

Recently, interfacing in low power devices has been successfully achieved by using the solutions based on the standard IPv6 over low power wireless personal area networks (6LoWPAN)[10]. Other proposed solutions, such as those in [11]-[13], achieved good results and could be suitably modified for use in home networks, particularly which involved middleware deployments to simplify the interfaces. Another solution for interfacing was the layered deployment of middleware to enable the Internet protocol (IP) connectivity through Zigbee as proposed in [14]. An approach considered mobile middleware agents to achieve the interfacing in [15], and the solution in [16] also catered to security issues.

An interesting approach is to introduce connectivity in medical sensor devices by coupling with Zigbee based technologies, interconnected with a bridge networking method[17]. Zigbee is based on the IEEE 802.15.4 stand for establishing low rate personal area networks which defines the physical and MAC layers with star and peer-to-peer topologies support[7]. It defines the network layer specification extending 802.15.4 functionality to tree and mesh based topologies[18]. On the other hand, Bluetooth based architectures have also been used because of low-power and low-cost requirements, to standardize interconnections between different devices. However, Bluetooth may not be suitable because of its non-reliability in communications, low range, and the complex method of enabling connectivity[19].

To address the problems of delay, data delivery, and power consumption in Bluetooth home networks, a protocol with features of simple pairing and inquiry response messaging has been proposed in [20]. These approaches, despite enlarging the scope of abilities to interface, deliberately adopt a loose approach to maintain generality towards multiple target environments. In general, there is not much innovation and effort needed to be deployed in a home setting, except for careful provisions regarding the data format[19] and the critical nature of timely readings.

2.1 Wireless Communications Technologies in IoT

There are a number of different wireless technologies that can be implemented in hardware products for green IoT and machine to machine (M2M) communications. Some of them are already established technologies while some are specifically developed to cater to the growing demand for IoT devices. We discuss some of the available technologies and corresponding advantages and disadvantages.

a) Wi-Fi (IEEE 802.11). Wi-Fi technology is based on the IEEE 802.11 standard and uses radio waves in the industrial, scientific, and medical (ISM) fields to allow two devices to communicate with one another. The technology is the most commonly used to connect Internet routers to devices like computers, tablets, and phones, which can be used to connect together any two hardware components. The IEEE 802.11n which was finalized in 2009 is a successor to the old IEEE 802.11g standard. It uses some new technology and at the same time tweaks the existing design to give a boost in performance and range. One of its new features is utilizing multiple wireless signals and antennas (called MIMO technology). MIMO uses several antennas to move multiple data streams from one place to another. Instead of sending and receiving a single stream of data, MIMO can simultaneously transmit up to three streams of data and receive two. Although it is a new technology, it still retains backward compatibility with the legacy 802.11 b/g.

b) ZigBee. ZigBee is targeted at control and sensor applications, and it extends IEEE 802.15.4 specification, which defines the only physical and MAC layers. Although the term “ZigBee” is often used interchangeably with “802.15.4”, this is not always true since devices that implement the 802.15.4 standard are not the automatic ZigBee compliance. Above the physical and MAC layers specified by 802.15.4, ZigBee describes the application support sublayer, network layer, and security layer specifications that enable interoperability between devices from different manufacturers.

c) Z-Wave. Z-Wave is a proprietary technology developed by a Danish company called Zensys mainly for the residential control and automation market. Theoretically, Z-Wave is intended to deliver a simple yet consistent method to wirelessly control appliances in the house, such as fans, lamps, and air-conditioning. The best attribute of Z-Wave devices is their cross compatibility among systems branded by different manufacturers. To make the system secure, every Z-Wave device has a special network identification (ID) and every network has a unique ID. Z-Wave devices also are very reliable, simple to set up, and very flexible.

d) Bluetooth low energy (BLE). The Bluetooth low energy is a new emerging ultra-low-power radio technology.

It is an open standard and used short range radio frequency. BLE is the hallmark feature of the latest Bluetooth 4.0 specification. BLE has been designed for ultralow-power applications, yet keeping similarities with the classic Bluetooth. Remarkably, a BLE implementation can reuse the classic Bluetooth circuitry components. Therefore, the upside potential for BLE is enormous given that future mobile phones that have a Bluetooth chipset are expected to include BLE as well.

e) INSTEON. INSTEON is a protocol developed for home automation by SmartLabs and promoted by the INSTEON Alliance. INSTEON is developed to integrate power line system with the wireless system, and is designed to replace the old X10 standard. It enables devices, whether sensors or switches to be used together using power line and/or radio frequency. Other than X10, this is the only technology that communicates via both wireless and power-line technologies. All INSTEON devices are peers, which means that any device can transmit, receive, or repeat other messages, without the need of a main controller. All devices resend and transmit the messages they obtain, except when they are the destination of the messages. This scheme can enable unsophisticated, low-cost devices to be connected together using the power line, radio frequency, or both.

Table 1 shows a comparison between different competing IoT technologies. After comparing the advantages and disadvantages, we select Wi-Fi communications as the technology of the choice because of easy interfacing with an available gateway device.

Table 1: Comparison between different IoT technologies

Technologies	Advantage	Disadvantage
Wi-Fi	High speed	Not suitable for battery power device
ZigBee	Low power	Low speed
Z-Wave	Low power	Closed source
Bluetooth low energy (BLE)	Low power	Small range
INSTEON	Has dual mode (wireless and wired)	complicated

2.2 Embedded Wi-Fi Modules Available in the Market

There are many Wi-Fi modules available in the market catering to a wide range of base technologies and audiences. The most popular Wi-Fi modules were surveyed to select one Wi-Fi module of choice. The most important selection parameters were 1) the cost of the module and 2) support for sleep mode or deep sleep mode.

a) ATMEL ATWINC1500. ATWINC1500 are highly integrated modules which will enable designers to lower their overall bill of materials while integrating IEEE 802.11 a/b/g wireless connectivity. The Wi-Fi modules will also provide an integrated software solution with application and security protocols such as transport layer security (TLS), integrated network services (transmission control protocol/Internet protocol (TCP/IP) stack) and standard real time operating systems (RTOS) which are all available via Atmel’s Studio 6 integrated development platform (IDP).

b) Bluegiga WF121. WF121 is a stand-alone Wi-Fi module providing fully integrated 2.4 GHz 802.11 b/g/n radio and a 32-bit microcontroller platform for the embedded applications. The module also provides flexible interfaces for connecting to various peripherals. It has an excellent RF performance, low power consumption, and compact size. WF121 allows the end-users applications to be embedded onto the on-board 32-bit microcontroller using a simple Bluegiga BGScriptTM scripting language without the need for the additional microcontrollers. WF121 can also be used in the modem-like mode in applications where the external microcontroller is needed.

c) ESP 8266. The ESP8266 module offers complete and self-contained Wi-Fi networking solutions and is designed for the needs of a new connected world. It can be used either to host the application or to offload all Wi-Fi networking functions from another application processor. ESP8266 has powerful on-board processing and storage capabilities that allow it to be integrated with the sensors and other application specific devices through its GPIOs with minimal development up-front and minimal loading during runtime. Its high degree of on-chip integration allows for minimal external circuitry, and the entire solution, including the front-end module, is designed to occupy minimal PCB area. The most powerful feature is its green feature that allows the Wi-Fi module to go into a deep sleep during a duty cycle. We selected the ESP8266 system-on-chip (SoC) module to develop our home energy monitoring prototype.

3. Design and Implementation

The main goal was to design and implement a system and a prototype capable to acquire energy related data after a few seconds so that energy consumption patterns could be studied. The prototype device is based on an earlier design in device prototyping[8]. In order to achieve this, we employed ATMEGA328 microcontroller to interface with an ESP8266 Wi-Fi SoC module, an AC transformer, as well as current transducers. The ESP8266 allows the microprocessor to connect to the Internet very easily through an established Wi-Fi connection, based on serial interfacing requirements. Arduino integrated development environment (IDE) was used to program the microcontroller to obtain energy measurements using an analog to digital converter (ADC) to interface with the sensors. Fig. 1 shows the block diagram of the components of the energy monitoring prototype. Five major components are used, which are power source module, microcontroller unit (MCU), ESP 8266 Wi-Fi module, ADC module, and a set of sensors. ADC is needed to convert the analog signal collected by the current transducer sensor and the transformer into a digital format before it can be processed by MCU. The main voltage is transformed down to a safe voltage level near 3 V before being applied to one of the analog inputs of the processor.

To integrate Wi-Fi capability into the device, the ESP8266 module was selected as the module due to recent popularity in IoT prototype research and low cost. A power source is needed to supply power to all the components based on their power requirements. For instance, the ESP8266 can only be powered by 3.3 V maximum. We consider Wi-Fi as the communication protocol of the choice instead of IEEE 802.15.4/ZigBee due to the ready availability of Wi-Fi networks in a house-hold setup. A traditional Wi-Fi gateway was used to forward the data from the prototype to the Internet.

3.1 Interfacing Between Module and Controller

The Arduino Mini Pro is used as the microcontroller platform as it is cheap, readily available, and compatible with many electronic modules. The microcontroller will be programmed to automatically send the AT command to the Wi-Fi module. The ESP 8266 SoC module employed in the embedded development is presented in Fig. 1. Arduino pin 3 will be set as the receiver (RX) and it is connected to ESP8266's transmitter (TX) while Arduino pin's 2 is set as the TX and it is connected to ESP8266's RX. Furthermore, the pin CH_PD, GPIO0, and GPIO2 must be pulled high and GPIO15 is pulled down before it can accept the AT commands.

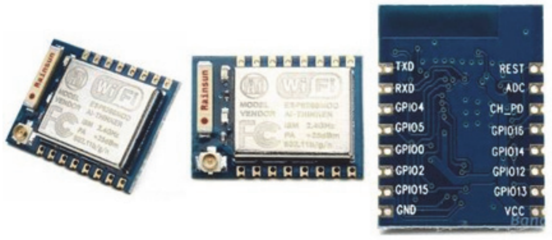

Fig. 1. ESP 07 Wi-Fi system on chip module.

3.2 AT Commands

The ESP8266 Wi-Fi module is programmed using the AT commands instruction set. AT commands can be sent through the serial universal asynchronous receiver/transmitter (UART) interface by connecting the ESP8266 to the Arduino Mini Pro Platform. Table 2 below shows some of the AT commands used.

3.3 Reduction of Energy Consumption

Fig. 2 shows the fabricated prototype whereas Fig. 3 shows the prototype during the breadboard stage. Achieving functionality and maximizing the lifetime of the sensors are conflicting goals. The most important requirement would be to limit the size of the data in an effort to preserve energy and set the optimum level of sensing frequency. The second method to preserve battery is to limit the transmission radius to a meter or so. However, due to the complex firmware limitation, the transmission radius modifications have been avoided, and the focus is laid on a simple method for the sensor to interact with the gateway.

The problem whether to save and archive all the data is up for the question. A list of privacy concerns and a proposed architecture have been documented in [21] and its authors have recommended keeping no central data storage. However, in the case of a home network, this will not enable the long term monitoring. Thus, the ability to store information about the energy consumption monitoring in a central location, for example, a server is essential.

Table 2: ESP8266 AT command set

AT Commands	Function
AT+RST	Restart
AT+GMR	Check firmware version
AT+GSLP	Enter deep-sleep mode
AT+CWLAP	List access points
AT+CWJAP	Join access point
AT+CWQAP	Quit access point
AT+CIFSR	Get IP address
AT+ CWSAP	Set parameters of access point
AT+CWMODE	Set Wi-Fi mode
AT+CIPSTART	Set up TCP or UDP connection
AT+ CIPMUX	TCP/UDP connections
AT+CWLIF	Check join devices' IP
AT+CIPSTATUS	TCP/IP connection status
AT+CIPSEND	Send TCP/IP data
AT+CIPCLOSE	Close TCP / UDP connection
AT+ CIPSERVER	Set as server
AT+CIPSTO	Set the server timeout
AT+CIOBAUD	Baud rate
AT+CIFSR	Check IP address
AT+CIUPDATE	Firmware upgrade (from cloud)

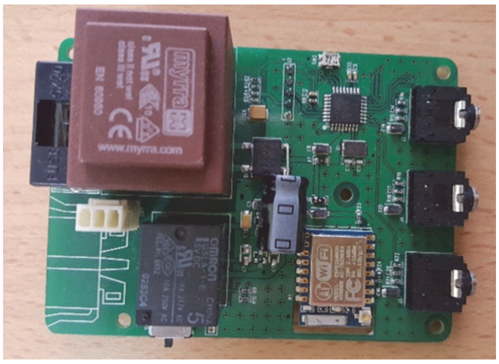

Fig. 2. Energy monitoring prototype after fabrication.

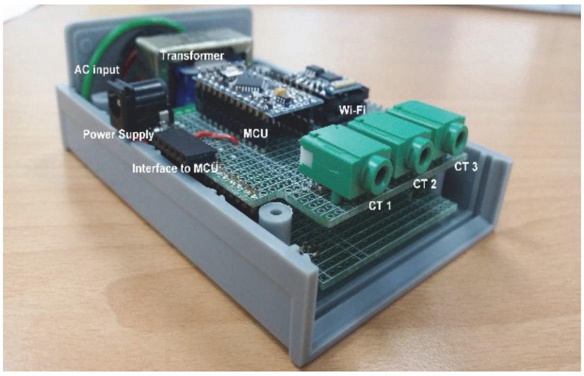

Fig. 3. Energy monitoring prototype during breadboard stage.

Fig. 4 shows the prototype operation flowchart. The sleep period is embedded in the ESP8266 Wi-Fi module by the manufacturer in order to reduce energy consumption. Hence, it is utilized here in this system design.

After obtaining the measurements, the equation in (1) is used to calculate the error for both prototype as well as Billion sensor devices with which the prototype error is being compared.

$$\text{Error}=\text{Source}-\text{Observed(Device)}. \quad (1)$$

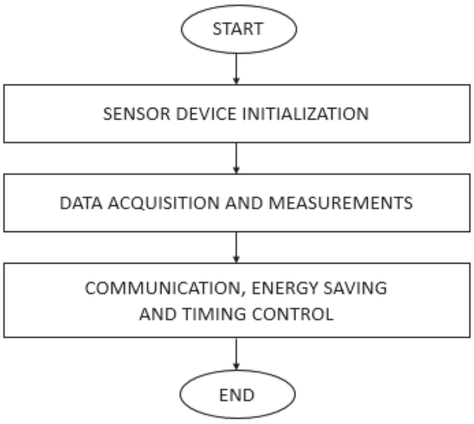

Fig. 4. Prototype operation flowchart.

A total of 100 samples were taken for the statistical estimation from the systems and compared with the actual value at the power source. The experiment was set up so that the simultaneous measurements from both prototypes and Billion sensors could be done. The source was assumed as the reference baseline for the measurements. The frequency of the measurements for the current was plotted in the y-axis for every increment of 0.005 in the error, which was plotted in the x-axis. For example, an error of 0.006 was rounded off to 0.005, whereas an error of 0.008 was rounded off to 0.01. For the voltage error distribution, a larger value (nearest 0.5) was used to round off the measurements, due to a lot of tiny fluctuations in the measured values, and the relatively large value of voltage (~240 V) as compared with the current values (~0 to 4 A).

The one sample Kolmogorov-Smirnov test procedure was used to compare the observed cumulative distribution function for the measured variables with a theoretical distribution. The distribution may be normal, uniform, or exponential. The two samples Kolmogorov-Smirnov test, based on the maximum absolute difference between the observed cumulative distribution functions for both samples, was also used. When this difference is significantly large, the two distributions are considered different.

4. Results and Discussion

This section presents the energy performance measurements of the final integrated device developed in the laboratory. The residential energy consumption results are not presented here due to privacy and data protection limitations.

4.1 Serial Monitor Output

The output of the device is monitored over the serial port and logged in a computer. This output plays an important role to detect any failure which will affect the subsequent data at the server as well. The device is configured to log important details such as sensor readings, Wi-Fi connectivity status, and server response and device state duration information in the log file for every sensing and transmission cycle. The time spent by the device in every state (sleep, idle, transmission) is also logged over the serial monitor. Once the connection with the server is established successfully, the sensor readings are retrieved and then a data packet is constructed. The data readings are transmitted to the server every 10 s.

4.2 Device Power Consumption

Due to the delay between subsequent data transmission, the device can be operated on a variable duty-cycle setting. The device supports two modes of operation, with and without the deep sleep mode. The deep sleep mode means that the device radio will be put to sleep after it has successfully sent the sensor data to the server for the remaining time of the 10 s cycle. On the other hand, the device will be put to the idle mode after data is successfully sent to the server. The operation of the device with the deep sleep mode consumes less energy than the one employing the idle state. As a comparison, we have measured and plotted the total power dissipation usage of the two modes of the operation of the device as shown below in Fig. 5 for one cycle of 10 s. The energy consumed in both the modes during the successful transmission of the data packet is the same (t={0, 4} s). The device connects to the Wi-Fi and establishes connection to the remote server during this duration. Upon receiving feedbacks from the server, the device now has the option to either go to the sleep mode or to the idle mode. The difference of power dissipation can be clearly seen in Fig. 5 between t=4 s to t=10 s.

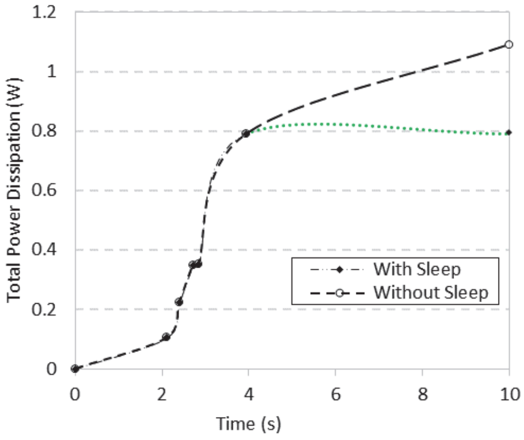

Fig. 5. Comparison of power consumption with and without sleep for one cycle of 10 s.

The difference of the power dissipation between the two modes is obvious and averages about 0.3 W. However, it is important to remember that this energy saving only applies a single loop of 10 s. The total operational lifetime of this device will be significantly longer than 10 s. Therefore, for a long operation time, this energy saving will be accumulated and result in better energy efficiency. Fig. 6 illustrates this idea by plotting the power consumption levels for 1 minute (6 cycles).

The average power dissipation of the device, however, fluctuates and increases slightly during the booting of the device as can be seen in Fig. 7. Over time, the average power consumption of the device is constant. A breakdown of the detailed power consumption of the device is presented in Fig. 8 where the actual fluctuation in power dissipation is displayed over a period of 350 s. The peaks correspond to the transmission of the data packet.

The support of the deep sleep mode for the ESP8266 Wi-Fi module is very important design criteria in selecting this Wi-Fi module because the energy usage is greatly optimized. In the long run, a large difference can be financially appreciated compared with the one without the deep sleep mode.

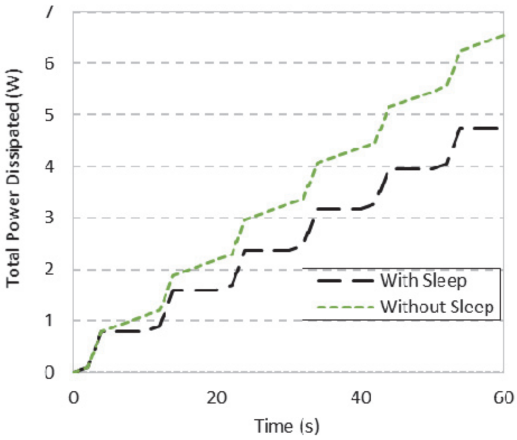

Fig. 6. Comparison of total power dissipation for one minute (6 cycles) period with and without sleep.

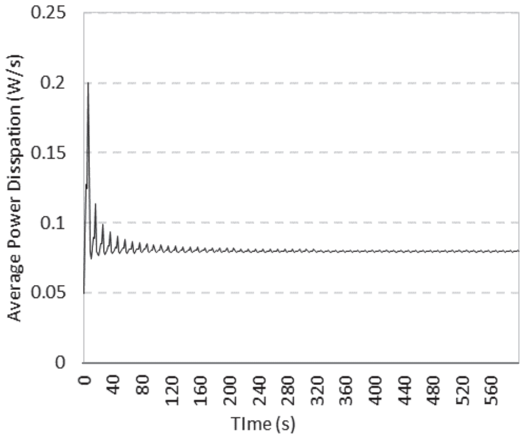

Fig. 7. Average power dissipation over a period of one hour from boot up.

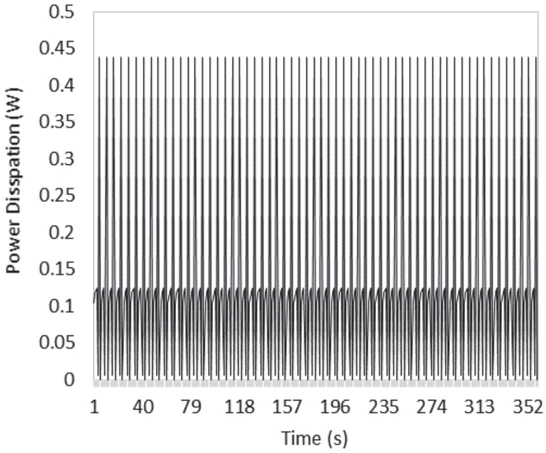

Fig. 8. Power dissipation pattern over the lifetime of the prototype.

In addition, it was found that both the Billion sensor and the proposed prototype produced a similar distribution i.e. skewed distribution, whereas Billion was observed to have a significant negative skewed distribution. The degree of skewness was investigated by using the one sample Kolmogorov-Smirnov test where both Billion and ELIVE did not meet the normality assumption (Asymptotic. Sig. (2-tailed)<0.05). Table 3 presents the error statistic comparison.

Table 3: Calibration error statistics between Billion and designed prototype

Iterms		Error (Billion)	Error (prototype)
N		100	100
Normal parameters (a, b)	Mean	−0.01270	−0.00240
	Std. deviation	0.00489	0.00355
Most extreme differences	Absolute	0.419	0.143
	Positive	0.271	0.124
	Negative	−0.419	−0.143
Kolmogorov-Smirnov Z		4.194	1.433
Asymp. Sig. (2-tailed)		0	0.033

5. Conclusions

A home energy monitoring device was developed which would continuously collect energy usage in home setup. This consumption data can be analyzed by the user to control, manage, and reduce their daily energy usage. For ease of market penetration, the IoT device was designed to use the Wi-Fi communication technology. To minimize the energy consumption in the process of monitoring the data, deep sleep methodology is implemented in the device. The system integration was successfully executed in a laboratory setting mimicking residential environment. The energy consumption performance of the prototype was evaluated as well.

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