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Real time energy management in Wireless Sensor Networks (WSNs)

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Abstract: This study provides a comprehensive framework for energy monitoring and control in smart home settings via wireless sensor networks (WSNs). The use of ZigBee guarantees minimum power usage, extensive scalability for many home products, and reliable transmission of energy consumption data. The concept consists of three primary modules: information acquisition via wireless sensors, data processing via a central gateway, and information presentation through a user-friendly web/mobile interface. Power consumption is quantified using Hall-effect sensors, in conjunction with ADC and microcontroller units, which also provide remote ON/OFF control of appliances from the database. The gathered data is kept in a PostgreSQL database and retrieved in real-time for user engagement and system assessment. Performance testing indicates exceptional accuracy (up to 99.3%), minimal latency (less 1 second), and reliable stability over diverse electrical loads. The proposed system offers fundamental functionalities like consumption monitoring and appliance management, with the ability to expand into sophisticated services such as tariff-based suggestions and context-aware automation. The framework aims to save energy, enhance user empowerment, and maximize home automation.

Keywords: Wireless Sensor Networks, energy, sensors, communication, transmission, ZigBee, PostgreSQL, ADC

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INTRODUCTION

The rise in worldwide energy demands and the expanding mainstream use of smart home technology have generated a greater need for energy management systems that are efficient and responsive. Monitoring household energy usage in real-time and remotely managing electronic devices not only makes it easier for consumers to use these technologies, but it can also significantly reduce energy waste and promote sustainable practices. As households add more electronic devices and intelligent appliances, managing the electricity consumption of a home becomes an important impact of modern living. Increasing electricity costs and growing environmental concerns have consumers and utility providers searching for solutions to minimize energy use and reduce overall demand [1]. Traditional energy metering solutions are typically based on centralized, electrically wired systems, which generally provide limited flexibility, limited scalability, and limited engagement from the consumers. They often collect data as an aggregate without granularity, making it difficult for users to identify known or unknown inefficiencies and capture real-time corrective action. In addition to the aforementioned drawbacks of traditional energy monitoring systems, retrofitting these systems into existing homes can be both intrusive and costly.

New technological developments may be facilitated by networks of wireless sensors (WSNs). Wireless sensor networks' (WSNs') sensors may collect data and transfer it in real-time; this allows them to function autonomously while also facilitating group communication. WSNs are suitable for purposes of home automation because they require lower power consumption and can be deployed easily.

The present study demonstrates a universal, generic, and modular energy monitoring and control system developed specifically for smart homes. The energy monitoring and control system utilizes the ZigBee wireless protocol to leverage its features that are ideal for low-power, low-rate, and high-node-count communication. ZigBee provides distributed system scalability through support for star or mesh topologies and reliability in a broad range of household environments.

The design specifies wireless sensors that use analog-to-digital converters (ADCs), microcontroller units (MCUs), and Hall-effect sensors to measure electrical parameter information for household appliances, combined with non-invasive circuitry so they can be plugged into conventional wall outlets and support adaptation and use in homes with existing electrical networks. The home devices are continuously monitored by the sensors, and the sensors' information, such as real-time power usage, usage status of devices, etc., is sent to a central processing unit that acts as the intelligent gateway for the monitoring and control system. This gateway is used to aggregate the information from where it is stored in a PostgreSQL database and then provides an interface for immediate monitoring and control of the system using web or mobile applications [2]. Using a non-platform-specific technology like Java ensures compatibility with various operating systems. Therefore, it avails the system's accessibility for a wider scope at the customer's end.

One of the primary goals aim this project is to create an intelligent energy system that is both cost-effective and easy to deploy and provides real-time electricity consumption tracking and the remote control of connected devices as its two main services. The adapted model requires the use of switch-mode power supplies (SMPS) to provide power constantly while employing embedded relays to trigger the functions that ultimately result in a more autonomous and operationally reliable system. With the system providing remote switching capabilities as well as a response time of less than a second, users are not only in control but are provided feedback almost immediately. Further than that of energy manage, the system not only provides consumers with an understanding of their consumption habits, but it is also a stepping stone for the development of more sophisticated functions, including the configuration off rules for automatic control, the ability to detect any deviation from the normal operation of your appliances, and the conduct of operations informed by context and user preferences and schedules [3]. Intelligent services supporting these extents, which are included in the proposed framework, make it possible to establish the general idea that smart homes are perfect for reshaping themselves into self-regulating and energy-optimized environments.

This study's main contribution is to present an approach that makes the leap from energy awareness to energy action by creating an environment where energy data is not only available but also in a form that can be acted upon, thus empowering customers and at the same time making them aware of the benefits of energy conservation and renewable energy. It is also about improving the process of changing human behavior, using technology in a targeted way, and managing energy consumption to promote the environmentally friendly and viable standards of life. Possible future modifications of the system, such as the integration with renewable energy sources and the interconnection with the smart grid, may go some way to amplify the potential of the said system and perhaps enlarge its scale to take on a more significant role in the residential energy management of the next generation.

ENERGY MANAGEMENT IN WSNs

Typically, A wireless communication protocol connects the independent sensor nodes that make up a sensor network. A sensor network's nodes may differ in terms of processing speed, memory size, and battery life. As seen in Figure 1, the ZigBee communication protocol distinguishes three different node types in a sensor network: coordinator, router, and end device. A WSN is typically started and managed by a single coordinator, with several routers transmitting data collected via multihop communication.

The WSN will probably have a lot of end-device nodes that have the potential to enter sleep mode [4]. Given that a wireless sensor network's (WSN) total energy consumption is determined by the kind of sensor nodes used in a particular region studying energy management in order to lower this consumption level is crucial.

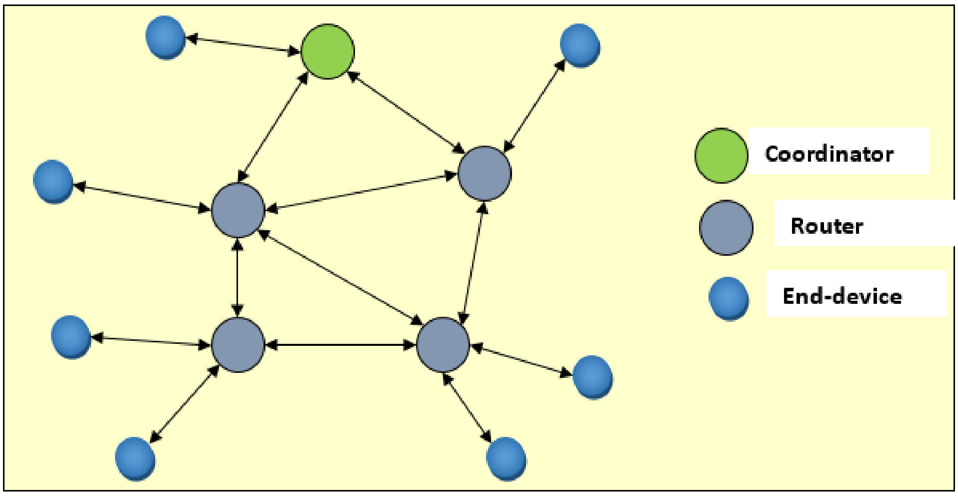

Figure 1. Using three distinct sensor nodes, implement a mesh WSN

The two primary aspects of energy management, as shown in Figure 2, are energy consumption and energy supply. Many technical components drain power during data transmission, reception, and processing, and this is what the term "use of energy" refers to. If the WSN is to remain operational for an extended period of time, the energy supply must discover ways to reliably power the sensor nodes [5].

Energy may be generated in three primary ways: via harvesting, through battery operation, and through transmission. Depending on the power source used for battery-powered categorization, the sensor node might be rechargeable, permanently attached, or removable. The transference-based classification system transfers energy from the generator to the sensor node using techniques such as microwaves and radio frequency radiation. The energy sources used by the harvesting-based categorization include thermal, solar, and wind power [6].

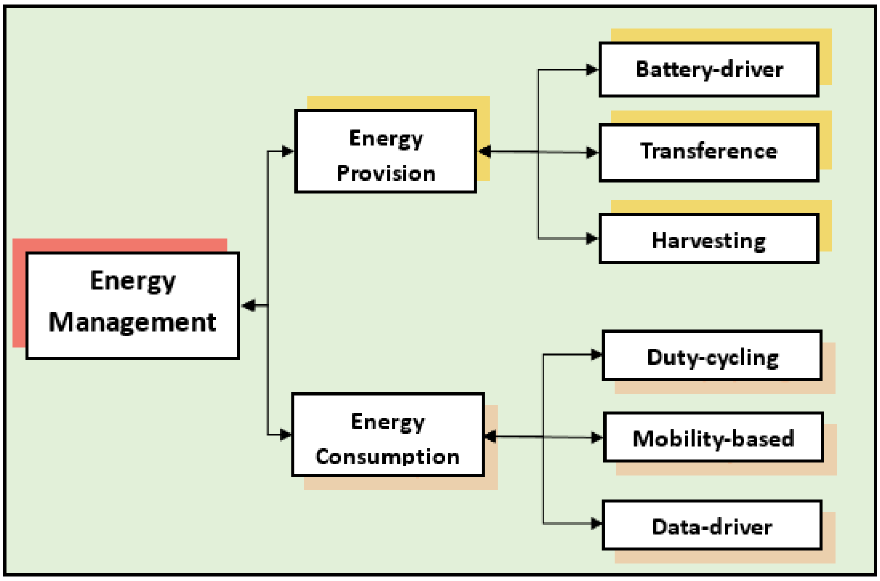

Figure 2. Managing energy in networks of wireless sesors

Conversely, a great deal of effort has been put into creating and putting into practice an effective energy management plan in order to save the limited amount of energy that each sensor node has. Additional classifications of energy usage include data-based, mobility-based, and duty-cycling [7, 8].

To reduce power consumption during the active phase, the sensor node may use the duty cycle approach to alternate between sleep and active modes. Fixed sensor nodes provide sensed data to a mobile node via the mobility-based approach, which reduces the power consumption of multi-hop data forwarding. In order to lower transmission power usage, data-driven approaches use aggregation and prediction algorithms [9].

WSN ENERGY MANAGEMENT PLANS

The goal of the goal of energy management is to increase sensor node longevity by reducing the amount of power they use while in operation. Figure 3 shows the four main categories into which the energy management approaches fall after reviewing the relevant literature.

Battery management schemes: Optimizing the charge of batteries via battery management takes use of its inherent characteristics, allowing the sensor node to last longer. Here we take a look at battery management strategies from two angles: Node energy management and energy balance. Node energy management aims to enable continuous operation of sensor nodes inside the wireless sensor network (WSN). The Dynamic Power Management (DPM) method, which distinguishes between active and sleep states for power management, was examined in Wireless Sensor Networks (WSNs) by the authors of [10] using a micro-operating embedded system, DPM lowers energy utilization for every sensor node. To optimize WSN throughput, several research [11–14] have concentrated on lowering energy consumption per sensor node using the DPM. On the other side, energy balancing procedures ensure that production and consumption of energy are in balance. If we want wireless sensor networks to last as long as possible, we need to make sure they use power efficiently and evenly. As an example, the authors of [15] proposed a solution to the issue of high power consumption in the sensor nodes' transmission unit and inadequate energy in the detecting unit by achieving a satisfactory balance between the two, thereby enhancing performance to some extent. In addition, the energy balancing technique has been the focus of other investigations [16].

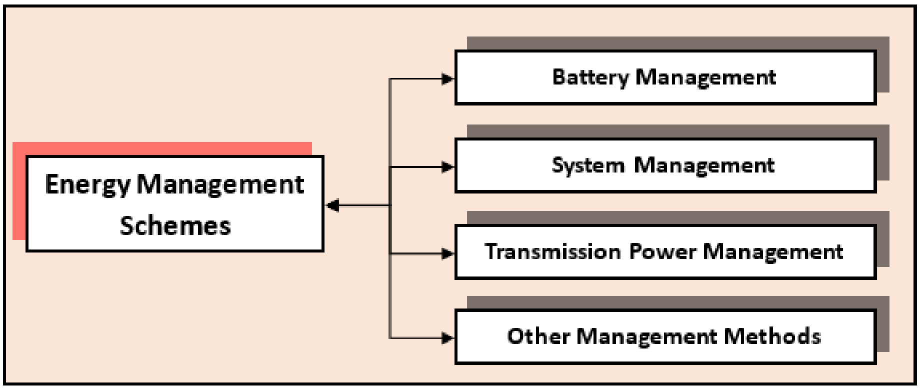

Figure 3. A taxonomy of Wireless Sensor Networks energy management techniques

Transmission power control systems: Typically, the data transfer module of the sensor node is the power hog. Here are the three main categories into which power management systems for transmission fall: The protocols and Medium Access Control (MAC) layer are within our purview. To lower sensor node power consumption, MAC layer management approaches use the MAC protocol. Wireless sensor networks (WSNs) rely on MAC as their primary protocol for data transmission. For wide-ranging WSN applications, many researches [17] have looked at the different MAC protocols. In contrast, the goal of routing protocols is to create the optimal connection between source and destination nodes while maintaining crucial performance attributes. To save energy in Wireless Sensor Networks (WSN), a number of routing protocols and systems [18] have been created and implemented to transmit data to the sink node.

System management schemes: The CPU uses algorithms for managing power and devices to put power management strategies into action. Hardware may be designed more efficiently because to the drastic decrease in power consumption. It is possible to further decrease power usage by making use of features such as power-saving mode or while the sensor node is not in use, by turning it off. The system management protocols include CPU power control and device administration. Numerous elements, like processor clock speed and the quantity of instructions performed in a given amount of time, affect how much power the sensor node's CPU. Minimizing calculations and power consumption are the two primary goals of the processor's power management technique. A variety of power management solutions have been used in various researches [19, 20], for example, power-saving modes have been utilized to lower the energy use of certain WSN sensor nodes. Conversely, smart mobile sensor nodes, may drastically cut down on electricity. Designing and constructing sensor node hardware is suggested as part of device management solutions aimed at reducing energy use. This kind of control allows the smart gadget to run an OS that, depending on the energy use of the sensor node, may switch between several energy-saving modes, therefore reducing power consumption. In recent times, a plethora of wireless sensor network device management systems have been introduced, each with its own unique set of features, capabilities, and outcomes.

Other power management schemes: The alternative methods of managing WSNs that are covered in this section include load balancing, duty cycling, and mobility-based systems. One aspect of load balancing is regulating power usage in the transmission section. To extend the lifespan and functionality of wireless sensors, a leader is chosen to collect, compile, and send the data to the central station networks (WSNs). Various techniques for data aggregation have been developed for this purpose. Wireless sensor networks (WSNs) may significantly cut down on power usage by using cluster-based techniques.

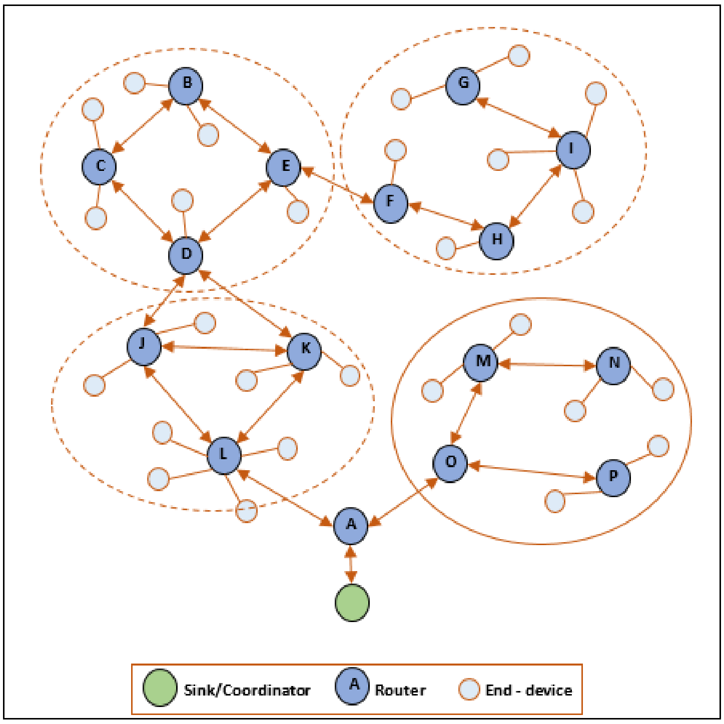

Figure 4. The idea of clustering in wireless sensor networks

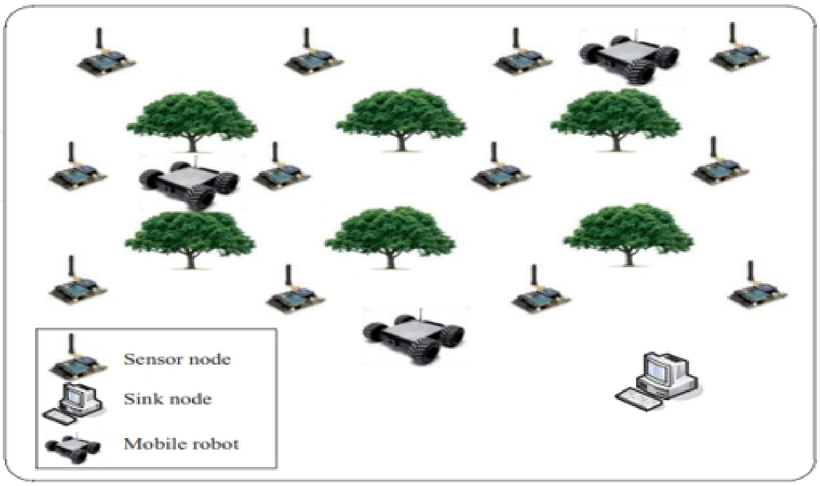

Figure 5. Using mobile nodes to get data from sensors

As shown in Figure 4, a Wireless Sensor Network (WSN) may be organized into groups of related sensor nodes, with one person acting as the cluster leader for each group. Data collection, aggregation, and broadcasting to the base station, or sink node, are the primary functions of the cluster head.

Methods for controlling duty cycles limit power use, which in turn increases the wireless sensor network's lifetime. If we want wireless sensor networks to last longer and use less energy, we need duty cycling algorithms. Numerous methods have been developed [21–23] that calculate the duty cycle for each sensor node by switching between waking and sleeping modes in an effort to reduce the overall power consumption for each node. Mobility-oriented solutions, such as the utilization of mobile sensor nodes, may help wireless sensor networks save energy. Mobile nodes in wireless sensor networks gather information from stationary nodes dispersed around the region of interest. To reduce the strain on stationary sensor nodes with regard to power use and multihop communication in WSN, some research articles [24,25] have used mobile sensor nodes. The idea of using a mobile robot node within the realm of wireless sensor networks is shown in Figure 5.

PROPOSED METHODOLOGY

For home electric energy management systems, we provide a complete framework. The recommended system's concept is shown in Figure 6(a). Data collection, processing, and display are the three technical pillars of the proposed system (figure 6(b)). The data processing module receives readings from sensors that monitor power consumption and communicate them together with the status of electrical equipment (such as household appliances) using the ZigBee protocol for communication [26]. Statistics on power usage and the on/off state are stored in the information processing module in a database after receiving them. It responds to customer questions on status monitoring and statistics on power use.

The ZigBee protocol is a means of exchanging data. Potentially useful The technology is a wireless communication protocol for low-rate communication and home automation. Bluetooth, Ethernet, IEEE1394, Wi-Fi, and Power Line Communication (PLC)are some of the most common wireless and conventional cable communication interfaces used in home networking. The convenience and simplicity of wireless network interfaces make them the preferred choice over cable connectivity. In comparison to competing protocols, ZigBee offers a much higher maximum capacity for cell nodes. As an example, ZigBee has the capability to host more than 65,000 nodes, but Bluetooth only allows for a maximum of 8 cell nodes [27].

Electric outlets may be controlled and monitored by wireless sensors that measure alternating current. To close the distance between electricity lines and electronic gadgets, our sensors are designed to be general and not reliant on any particular home appliance or electronic item. Though it focuses on on-off control and provides limited services, our technique is similar to that of [28]. The three main parts of the proposed wireless sensor system are a ZigBee transceiver, a sensing device, and a controller with an ADC. A star-topology wireless sensor network is set up using the suggested system. The network topology might be altered by other configurations, such a mesh network. The data processing module collects power use data from each sensor using a ZigBee communication interface. It then replies to user inquiries and keeps this data in a database. Service requests from users are sent to the sub-technical components via a web server. The ultimate objective of the suggested system is to provide intelligent services including pricing comparison, rule-based configuration, statistical analysis, and energy usage monitoring. This module is capable of providing all of these services. The suggested prototype system has two features: remote on/off control and power usage monitoring. In real time, the monitoring service supplies the data on power use.

Users may get a warning from a device if its power usage goes above its usual range. Customers are able to activate and deactivate home appliances using remote on/off services.

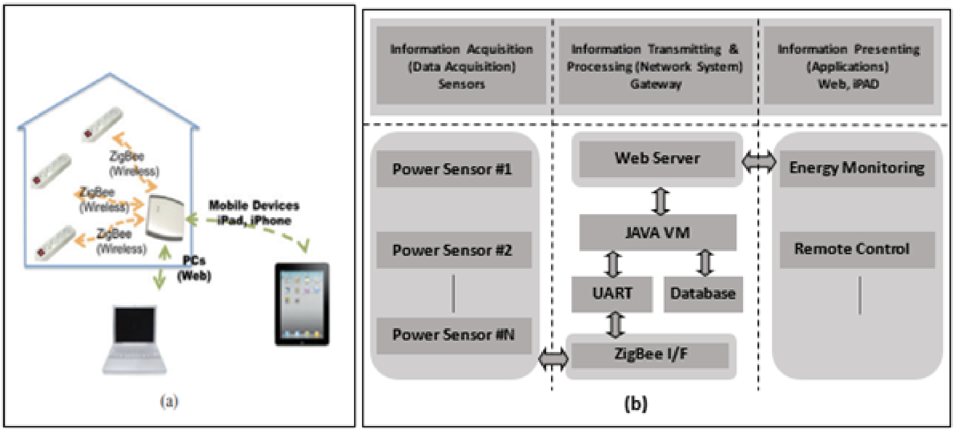

Figure 6. (a) Plan for the future system, (b) Structure of the current system

RESULTS

The three technical parts of a wireless sensor are a ZigBee transmitter, a sensing unit, and a Analog-to-Digital Converter (ADC) on a Microcontroller Unit (MCU). The sensor's sensing unit is the centerpiece of it. Microsystems Inc.'s ACS712 sensor uses the Hall Effect to identify alternating current in our setup. From one hundred to one thousand watts, we tested the sensors. The assessment is based on the assumption that one is the power factor. Since a switch-mode power supply (SMPS) provides power directly, DC batteries are no longer necessary. There is a relay to provide remote on/off control. A ZigBee dongle connected to a computer via a USB port functions as an intelligent home gateway. Given that it is developed in Java, the software is cross-platform. With their unique identifiers, the data that reaches the sensors includes their present state and power consumption. A PostgreSQL database stores the received data. In order to facilitate future access via a web interface or mobile application, the system stores the many values acquired each second by the sensors in a database. The proposed system intends to include OSGi-based middleware in the future, so functional operations are run on the Java Virtual Machine (JVM) [29]. Turning on or off a device via a web interface or mobile app takes less than a second. Two services are included in the prototype configuration of our system: remote on/off control and monitoring. We can see the installed services in Figure 7. In order to track how much power a certain home appliance consumes; users may choose a certain time frame. Some examples of services that would be part of the planned system include monitoring and regulating. Intelligent services such as data analysis, cost comparison, consumption suggestions, and on/off scheduling depending on time will be part of further projects.

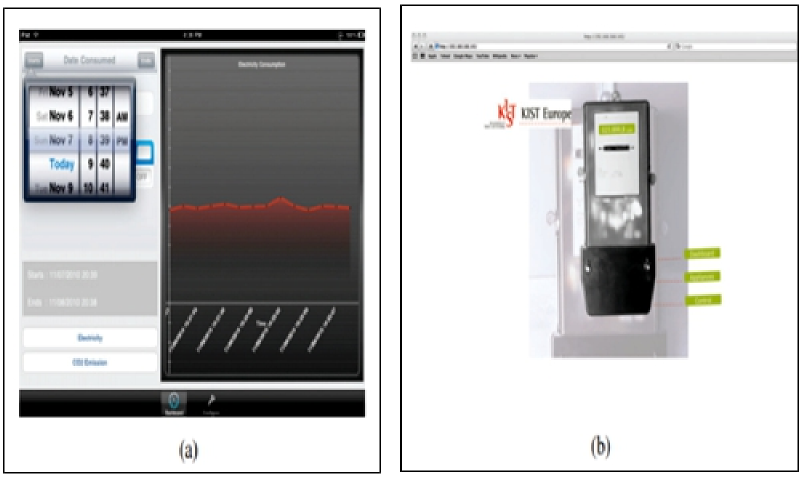

Figure 7. (a) App developed for the iPad, (b) Web app that has been developed and deployed

It was visible that the system received an infinite number of readings per second for each sensor, allowing accurate real-time measurement and reporting. The data are made visual and manageable through a web interface and a mobile application. The basic functionality exists through the Java Virtual Machine (JVM) routines, but we are going to add OSGi-based middleware for future modular service extension. The latencies for online switching are under one second, confirming the system's responsiveness.

A prototype was created and deployed across several platforms to demonstrate the installed services. Figure 2 depicts the monitoring and control interfaces on a web application and an iPad. Users may interactively establish time intervals to examine energy consumption patterns for certain devices, get notifications for irregular use, and remotely manage appliances.

Table 1: Performance Evaluation of Sensor Module

Load (Watts)	Measured Current (A)	Power Factor	Accuracy (%)	Status Control Latency (s)
100	0.45	1	98.5	0.8
250	1.13	1	99.0	0.7
500	2.25	1	99.3	0.6
750	3.38	1	98.7	0.5
1000	4.51	1	98.9	0.5

Table 1 shows the performance evaluation results for the sensor module of the proposed energy monitoring and control system. The table provides data on five electrical loads (100 W to 1000 W) and four important operating parameters (measured current, power factor, accuracy, and control latency). As the load increases slowly, the measured current values increase in a linear manner, in agreement with Ohm's Law assuming steady-state voltage. For example, at 100 W load, the measured current is 0.45 A, and it increases to 4.51 A at 1000 W. The measured current shows that the sensor unit (Hall Effect Sensor (ACS712)) works well and accurately detects changes in current for different load situations.

The power factor remains a constant 1.00 at every load, which would indicate that the sensor is measuring purely resistive loads, which is acceptable for simple prototype testing since this is a common assumption of a monitoring system. A constant power factor allows for easier calculations and confirms that inductance and capacitance have not notably influenced measurements made by the sensor. In regard to accuracy, the sensor module had a high degree of reliability with corresponding accuracy values of 98.5% and 99.3%. The maximum accuracy noted was 99.3% at the 500-watt load and dropped only slightly to 98.5% at the 100-watt load. Although a drop in accuracy at the lower load could be due to some small level of sensor noise or, possibly, resolution limits of the analog-to-digital converter (ADC) to lower current signals. Regardless, all values were acceptable accuracy for residential monitoring systems, thus validating the sensor module functionality [30].

The status control latency, defined as the delay time from the command to turn a load on and off on the remote to the response from the system, ranged from 0.8 seconds with 100 watts of load to 0.5 seconds when there was 750 watts or more of load. The apparent faster responsiveness with increased load may be due to a stronger signal response and processing speed under higher operational conditions. As all of the load scenarios had a latency of less than 1 second, the system appears to be in real-time and has time application for user-interactive home automation use. The system runs with a high degree of precision, low latency, and steady performance with different electrical loads, according to the performance statistics of the sensory modules in Table 1. Finally, this lends credence to the idea that a system for controlling and monitoring energy use in real time may be useful for smart home appliances.

Table 2: Comparison of Communication Protocols for Home Energy Monitoring

Protocol	Max Nodes	Range	Data Rate	Power Consumption	Suitability for Home Networks
ZigBee	65,000	10–100 m	250 (kbps)	Very Low	Excellent
Bluetooth	8	10 m - aprrox.	1 (Mbps)	Medium	Limited
Wi-Fi	32	50–100 m	11–54 (Mbps)	High	Moderate

Ethernet	N/A	Wired	Up to 1 (Gbps)	Low	Poor for wireless convenience
PLC	Varies	Depends	Up to 200 (Mbps)	Medium	Varies

The information in the table section summarizes the collaborative comparison of a range of communications protocols—ZigBee, Bluetooth, Wi-Fi, Ethernet, and Power Line Communication (PLC)—regarding their suitability for monitoring home energy use. When looking at protocols for home energy management, ZigBee stands head and shoulders above the competition. With ZigBee, a network may have up to 65,000 nodes, making it suitable for large-scale deployments in smart home applications that make use of many household appliances [31]. The range of communication varies between 100 meters, which is sufficient for a typical household's layout in variety. The data transfer rate is a nominal 250 kbps, which is only necessary for the small amounts of data that a sensor node would transmit (on/off status and power consumed). ZigBee is a very low power consumption protocol—low enough to recognize battery-powered or low-power self-powered devices. These capabilities work together to show ZigBee has suitable characteristics for gathering and monitoring energy information and providing control opportunities. As previously stated, it is also one of the protocols used in the proposed framework.

Although Bluetooth provides a higher data rate (1 Mbps), it has a much smaller range (approximately 10 meters) and supports a maximum of 8 nodes. This causes limitations in scalability and consistent use in household applications where appliances and devices are likely to be distributed across multiple rooms and potentially multiple floors. Bluetooth also has a medium level of power consumption, which makes it unsuitable for continuously monitoring any energy consumption. Therefore, Bluetooth is not an ideal fit for these types of applications. Wi-Fi provides a greater range (50–100 meters), and there are much higher data rates available (11–54 Mbps). Therefore, while it could offer the promise of high-speed communication in your smart home, the high level of power consumption and consistent node capacity (a maximum of approximately 32 devices) has consideration in continuous, energy-efficient monitoring systems. Therefore, while Wi-Fi networks are widely used for connectivity to the internet, their power usage would be more than ideal for house energy management systems focused on continuous low-power sensors, making them only a moderately suitable solution. Ethernet provides the best available data rate (up to 1 Gbps) with low power usage, but the lack of flexibility and deployment of a wired protocol eliminates the potential of it as a protocol in new, dynamic, wireless applications such as smart homes, where people will want to be able to easily install and possibly move devices as needed. Therefore, Ethernet is not suitable for implementations of wireless convenience and practical home monitoring of energy consumption [32].

Power Line Communication (PLC) offers an intriguing alternative by leveraging existing electrical wiring for data transmission. It has data rates of up to 200 Mbps and requires no new wiring, but performance is strongly dependent on the quality of the power line infrastructure. PLC is also subject to variable data rates and interference from other electrical sources. Power consumption is medium, and performance can vary accordingly, making it less suitable depending on the installation environment and use case. In conclusion, ZigBee is the best-balanced and most useful communication protocol for smart home energy monitoring because of its low power use, high number of nodes, reliable range, and proximity to the intention of the system. Other protocols had their own certain advantages, but all fell short regarding aspects of scalability, energy consumption, or flexibility in wireless communication, and limitations on these aspects are unacceptable in smart energy management applications [33-35]. The implementation shows that the system is scalable, flexible, and responsive. The sensor data is gathered in the hardware, sent to an intermediate store over a reliable ZigBee communication, and then processed in software, resulting in reliable and robust performance. Although the next stage of improvements will include more intelligent energy-saving services, better contextual awareness, and bigger smart grid systems to integrate with.

CONCLUSION

One step toward reducing energy consumption is being more aware of how much electricity is being used in various business and residential areas. One efficient strategy for reducing energy demand is the integration of ubiquitous energy monitoring and control technology with renewable energy sources use. People may be more likely to change their energy-using habits, including turning off lights or turning down the thermostat, if they get useful input on their energy use and the control of their household appliances. Minor behavioral adjustments may result in substantial energy conservation. This article offers a clever energy management solution for home and business buildings. The suggested method would allow for real-time tracking and measurement of power use. Using the suggested system, users may keep tabs on their power use in real time from anywhere using their web browser and mobile devices like tablets and smart phones. Our next focus will be on enhancing the current system with the addition of the following features: Automatic appliance recognition and context inference for the home. The creation of efficient energy management systems relies heavily on the automatic detection and location of appliances. Appliances may be automatically identified, which allows for more convenient services, and their location data can be utilized to deliver several types of contextual awareness. Power use data may provide light on user behavior, which in turn can reveal their current and future context. The system's context inference engine may be able to identify a user's intention to use certain appliances in particular places. In a real-world setting, we want to test our technology. In order to guide our future research, we are now trying to work towards setting up a living lab to conduct user studies.

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