Development of Open-source Low-cost Building Monitoring Sensors using IoT Standards

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Abstract

Energy consumption has dramatically increased in the residential building sector over the past few years. Many researchers today are interested not only in designing energy-efficient buildings but also in evaluating the actual building performance and managing operations for delivering the design intent. Monitoring building performance using currently available sensors and mobile applications poses challenges in terms of cost and standardization. This paper presents a new approach to make sensors affordable and inter-operable by designing open-source hardware and using well-established standards for data communication and storage, thereby making energy monitoring ubiquitous and affordable in the residential sector. The proposed solution uses low-power loggers, Bluetooth Low Energy wireless communication version 4 for data transfer from loggers to mobile phones for further transfer to cloud, oneM2M standard to ensure interoperability, and NGSI-LD for data management.

I. Introduction

With the rapid growth in urbanization, rising income, and growing population, the building energy consumption in India is also growing at a fast rate. The high energy usage in buildings is due to end-use demand for heating, cooling, ventilation and lighting [1] [2]. Therefore, it is important to monitor energy usage and building performance to achieve energy-efficient buildings without compromising the occupants' need for thermal and visual comfort. Studies have also shown that proper operations for buildings can lead to 10% to 30% savings in energy utilization [3][4].

The green building revolution is transforming the marketplace for commercial and residential buildings to form better sustainable environments. It aims to change the build environment by creating healthy, energy-efficient and productive buildings that significantly reduce the impact on global climatic change and energy utilization [5]. Lately, the emphasis has been on monitoring the actual energy performance of buildings to ensure design intent is met. To curb energy consumption in buildings, many organizations have come forward to perform energy audits and 'certify' or rate buildings based on building energy efficiency. Similar to the BEE star labelling system [6], which evaluates the energy efficiency of buildings, councils such as IGBC [7], GRIHA [8] and LEED-India [9] have evolved for buildings. Buildings certified by the green rating systems have a requirement that the minimum energy-efficiency codes, such as Energy Conservation Building Code (ECBC) or American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE) 90.1 are complied. Also, the current theme for ASHRAE in 2019-20 is on 'Building for people and performance. Achieving operational Excellence' [10].

The Indoor Environment and energy performance in commercial buildings is monitored using a Building Management System (BMS), and with sensors incorporated in the building. However, their application becomes challenging for residential buildings because of the high cost of BMS and lack of standardization in low cost sensors and loggers. Some of the parameters that researchers and building owners tend to monitor are indoor temperature, humidity, CO_2, and PM2.5 along with energy and power consumption for individual devices (sub-metering). These sensors operate on varied protocols, with different power sources and communication media, complicating the subsequent communication of data to the cloud. Further, the power requirements (input voltage and current levels) for these components can be different, making the power management circuitry on these boards challenging. Juggling various communication protocols and power requirements add to the cost, complexity and maintenance of the final system.

Given this context, this paper discusses how the issues mentioned above can be addressed using the approach of open hardware and software design and data standardization.

II. Development of Low-cost Sensor

Smart energy monitoring applications use embedded devices to collect information related to energy use and Indoor Environment Quality (IEQ). Different manufacturers design and develop these devices for use in residential buildings. The devices currently available in the market for data logging have a variety of selection criteria:

- *Communication:* wiredor wireless (GSM, Wi-Fi, Z-Wave, BLE, LoRa etc.)
- Power: battery operated or mains-operated
- *Logging:* duration and data rate may vary from device to device (with/without real-time clock)
- *Protocols:* proprietary, standard IoT
- *Storage:* on-board, connected computer or cloud
- *Storage-type:* proprietary, standard
- *Visualization:* web-based dashboards, mobile applications
- *Installation:* clip-on, rail-mounted

Due to these variations, there is a large variety of available sensors. Communication protocols used in different loggers may vary according to the manufacturer. Loggers that use GSM for data collection provide uninterrupted internet connectivity, however, they require a lot of power to be operated continuously and also involve recurring costs for continuous internet connectivity. Replacing them with Wi-Fi, Z-wave reduces the power requirement but leads to the need for additional devices such as routers and gateways for data transfer. Though Wi-Fi based data collection methods are cost-efficient and user-friendly, they have not been recommended because house owners may be hesitant to share internet for data collection. It is evident that there is a need for wireless, low powered, cost-efficient data loggers that can easily communicate with a mobile app, based on industry standards for communication and data storage.

In addition, data collection involves the generation of data in different formats with various logging intervals. Storage of the collected data across a variety of cloud platforms makes it further difficult to access data because data sharing across platforms require complex application program interfaces (APIs) to convert data from one format to another. Also, data access permissions may vary across platforms and application. A system, comprising cloud storage, analytics engine, and software and mobile applications may be built on different technology platforms, therefore generating different output formats. In addition, manufacturers either provide mobile applications or APIs to access or store the monitoring data. This data can be viewed on mobile devices, downloaded on local machines or pushed to the cloud or web servers for further processing and analysis. Using these manufacturer-specific solutions to measure different criteria for building performance, poses the following challenges:

- Limited availability of standard, low-cost data loggers to suit the need of researchers, building auditors, and students
- Unavailability of datasets in open formats for research on building performance

These challenges lead to the need for an open and interoperable solution that will ease data logging, data collection, and sharing of datasets among different users.

III. Proposed Solution

From the current available wireless technologies, Bluetooth Low Energy (BLE) is the best choice for the proposed solution because low-power and low-data network is the fundamental feature required from the loggers. BLE is designed to transmit/receive data in a personal area network while consuming extremely low power. It operates in the 2.4 GHz ISM band using Gaussian Frequency Shift Keying (GFSK). It is supported by mobile phones and tablets, making it an ideal solution for interfacing the logger to a mobile app and capturing data at different intervals based on the user's choice. In addition to a cloud storage service, we integrated an on-board memory chip of 4 MB capacity. This helps store data up to one-year avoiding data losses if any. Adding clamps, magnets or zip tags to the loggers makes installation and mounting easy for both homeowners and surveyors. The design approach presented is generic to any embedded device that is used to monitor any parameter: temperature, humidity, CO_2, energy, current at the residential unit or appliance-level.

a. Open-source Hardware

The proposed low-cost, low-energy data logger designed using the proposed approach has six subsystems as described below (taking current logger as an example). *Figure 1* depicts the open-source hardware module.

- *Current transformer:* The current transformer used is XH-SCT-T10. It is a 50A to 0.33V equivalent voltage output current transformer. It is rated for input current from up to 100A with an accuracy of 1% over 5% to 120% rated current.
- *Analog to Digital Converter:* MCP3919 analog to digital converter from Microchip is used to convert the analog voltage from the current transformer to digital signals. It has three synchronous channels with 24-bit delta-sigma analog to digital converter. With this ADC, we can have a simultaneous sampling of 3-phase current. Its low power consumption (<6mA at 3.3V) makes it an appropriate component for a low power analog data acquisition device. The data acquired using the ADC can be readout using a high speed 20 MHz Serial Peripheral Interface (SPI) provided on the ADC.
- *Microcontroller with Bluetooth Low Energy Subsystem:* At the core of the design, we used NRF52832 from Nordic semiconductors as the microcontroller. It is a multi-protocol System on Chip (SoC) that supports Bluetooth 5 and Bluetooth mesh. It is built around an ARM® Cortex™-M4 CPU with the floating-point unit running at 64 MHz. It can achieve a very low power consumption as it has an on-chip adaptive power management system.
- *Flash Memory:* To log the data internally, a flash memory from Winbond Electronics (W25Q32JVSSIQ) was interfaced with the microcontroller through the serial peripheral interface. It has 4 MB storage with 66 MB/s continuous data transfer and over 20-year data retention.
- *Real-time Clock:* The MCP7940N Real-time Clock/Calendar (RTCC) tracks time using internal counters for hours, minutes,

seconds, days, months, years, and day of the week. Alarms can be configured on all counters up to and including months. For usage and configuration, the MCP7940N supports I2C communications up to 400 kHz.

- *Boost Converter:* The MAX17220–MAX17225 is a family of ultra-low quiescent current boost (step-up) DC-DC converters with a 225mA/0.5A/1A peak inductor current. It helps in keeping the device running at a very low voltage range up to 0.8 voltage from two AA Batteries.

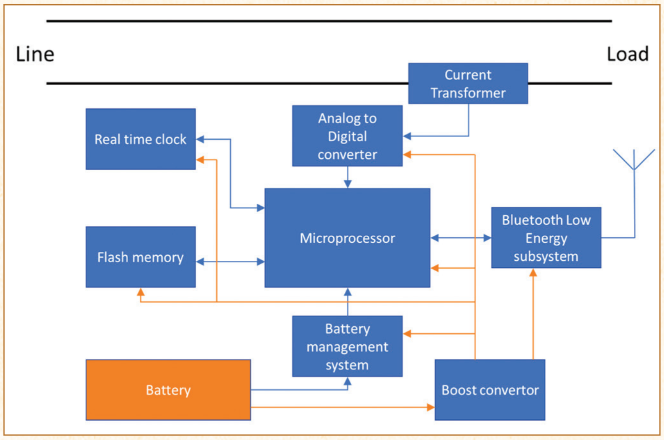

Figure 1: Block diagram of the open-source hardware module; blue lines indicate data connections and orange lines indicate power supply

System Firmware

- *Configuration:* The functional units of the proposed logger are arranged such that it consists of three major units: current measurement unit, power unit, and the communication unit.
  - The *current measurement unit* contains a *Current Transformer and an ADC (Analog to Digital Converter).* The transformer produces a proportional amount of alternating current on its secondary winding which is flowing through the wire that acts as a primary winding. Such a setup reduces the high current flowing through the wire to the proportional value of the winding ratio. The ADC has three synchronous samplings 24-bit resolution Delta-Sigma A/D converters, which are used to read the data from the current transformer and apply a gain factor.
  - The *power unit* uses the boost converter. It is a highly efficient DC-DC converter. It has a current limit and true shut down feature, which helps in running the device at a very low voltage of 0.8V. However, the internal converter gets deactivated, and the LDO keeps running during deep sleep.
  - The BLE is a part of the *communication unit.* The user connects to the data stored and retrieves the data through this RF front end. It exposes GATT UUIDs for the user to connect and interact.
- *Operation:* The firmware performs three basic operations.
  - The device shifts to a deep *sleep mode* when the device is not operational. This helps in maintaining the battery charge.
  - The *data acquisition* operation is responsible for reading data from ADC, maintaining a sleep and wake-up cycle and advertising the Gap profile. The acquisition process is done in a window of 80 ms. During this interval, the ADC is brought to an active state. As the ADC has the three simultaneous channel data sampling capability, the data sampling for the three phases is done in the same instant. After ADC reads the data, an automatic gain adjustment is done. It has two stages:
    - When the read current value is less than 400mA, an appropriate gain factor is applied.
    - If the read current is >400mA, another gain factor is applied.

    This auto gain is applied on each of the channels independent of each other. After the auto gain is applied on data, a running average of the data is done for an interval of 1 min. This step is repeated on every data point. A buffer for data of 40 min is maintained with the SoC cache. This is then written on to the flash memory.
  - The *data* from the logger is downloaded using the BLE notifications. There are 3 UUIDs on which the user performs the read write operation. One UUID shows the number of records present in the logger. To initiate the data download, the user inputs the password for the device. Once the user is authenticated, the BLE notification can be enabled. Depending on the count, the user inputs the starting count and ending count from where the user wants to read the data. Once the starting and ending record is set, the device pushes the data using the notification option to the user.

Further, the device is fabricated with the following mounting options:

- Magnets on the back of the logger case to mount it to the metallic distribution box
- The DIN rail mounting present on the back to mount on to the DIN rail of the distribution box
- Double-sided tape to affix the logger to a surface
- Zip tags to fasten the logger onto the board with the mounting holes present on the clips

b. Open-source Software Framework

To tackle the challenges faced in data access, processing, and storage, a three-layered model has been adopted [11] [12]. This model will accelerate and facilitate device-data control and management operations. The layers are:

- Physical layer – interfaced by Southbound APIs
- Data lakes, and
- Applications – interfaced by Northbound APIs

The *physical layer* consists of low-cost sensors and data loggers. These devices gather information from the surrounding environments in order to be used by various applications. The microcontroller present in the devices is responsible for collecting, combing, organizing and communicating the data via Bluetooth to the mobile application using the Southbound

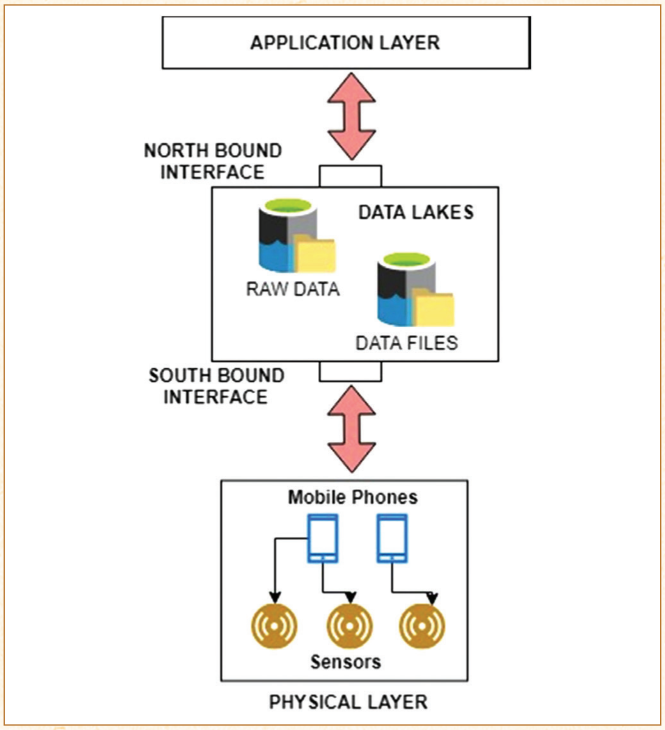

Figure 2: Interactions between different layers of the proposed system

APIs. Sensor type, sensor location and other sensor metadata are also communicated to the data lake. *Data Lake* is a centralized repository used to store structured as well as unstructured data related to device configuration and sensor values. It can also be used to run different types of analytics, provide visualizations, and apply machine learning for better decision making. The Southbound APIs are responsible for lower layer interactions between the data lake and the sensor devices. The application layer is combined with user applications, which facilitate access to the stored data and act upon them if necessary, through the Northbound Interfaces. The Northbound APIs are responsible for communication between the applications and the data lake. *Figure 2* depicts these details.

Presently, many researchers are working on a similar standardization in the domain of Internet of Things (IoT) [13] [14] [15] [16]. The rapid evolution in IoT led to a wide variety of solutions focusing on different industries. Most of the solutions used hardware devices and connected them to the relevant cloud services making them vendor specific. This led to lack of consistency and standards for communication and storage bringing up the need for IoT standardization that would enable seamless resource sharing between different vendors, academia, and industries [17][18][19].

oneM2M is one such standardization solution that has ensured successful interoperability, which is adopted at our model's Southbound Interfaces [20]. It has been developed by the oneM2M partnership project that consists of eight of the world's foremost national standardization bodies along with industry partners. oneM2M provides a common set of service functions and communication protocols to access the device data, data sharing and semantic interoperability. It is also aware of optimizations such as power saving and triggering/wakeup of devices without the need for the developer to be aware of these terms.

NGSI-LD is another proposed solution for IoT standardization developed by ETSI to manage context information [21] [22]. The FIWARE is a version of the NGSI interface that uses open RESTful APIs via HTTP to exchange context information about context entities in the form of:

- One-time queries or
- Subscriptions/ notifications about context information updates

NGSI-LD provides a scalable solution to connect, publish and federate diverse data sources using a developer-friendly interface for data sharing and usage. The data in NGSI-LD is like a data graph model and linked with each other. Use of NGSIv2 as a northbound interface provides a developer-friendly API design to send and receive data across layers and to-and-from the data lake.

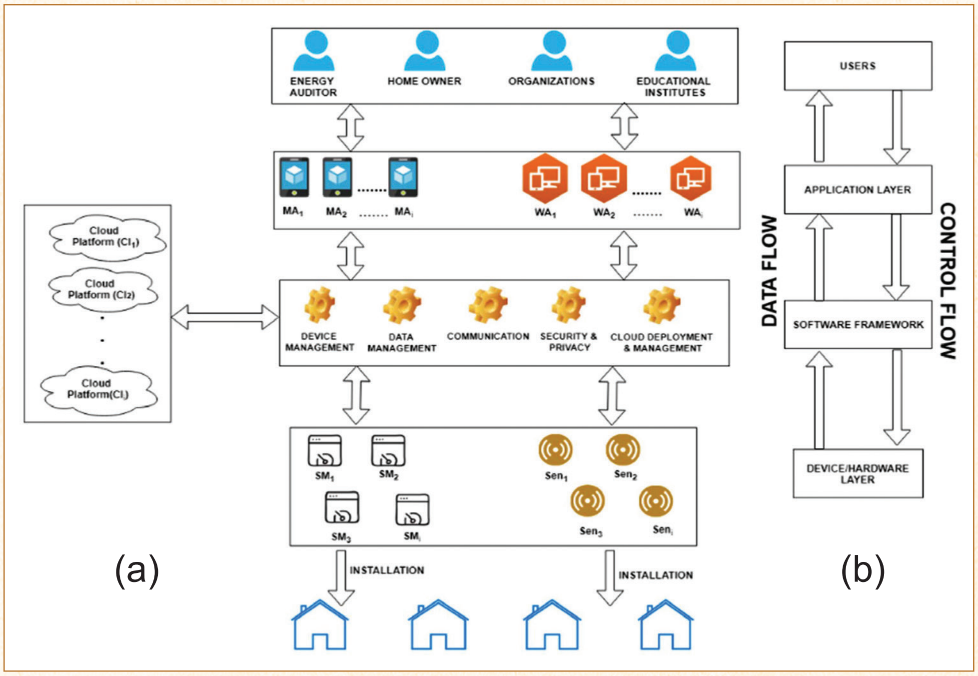

Figure 3: (a) A high-level view of workflow for the proposed model, (b) Flow of sensor data and control signals

Figure 3 demonstrates the workflow of the proposed model for residential energy monitoring. Description of the terms used in the figure are:

- CI_1 to CI_i represent Cloud Platforms for data storage.
- SM_1 to SM_i and Sen_1 to Sen_i represent the Smart Meter Loggers that log the kWh data and the sensors that capture indoor environment temperature, humidity, CO_2 levels etc.
- MA_1 to MA_i and WA_1 to WA_i represent the Mobile Applications and Web Application provided by the various device manufacturers to view the information.

The proposed workflow is as follows: Once the desired house is identified and selected, a unique house ID is assigned, and data loggers and sensors (like Garud current logger) are installed. The *device management and communication* services present in the software framework ensure that the device IDs of these loggers are mapped to the respective house IDs using BLE as a communication interface. The service also makes sure to return the MAC address of the logger and encrypted device password when the barcode on the device is scanned using the mobile app. Once the data is ready to download, the BLE on both the logger and mobile phone app are activated to connect to each other and fetch the data. *Data management service* downloads the data locally to the mobile app in an encrypted format and sends it to the cloud for further processing, visualization and analysis that will help in decision-making and designing predictive models.

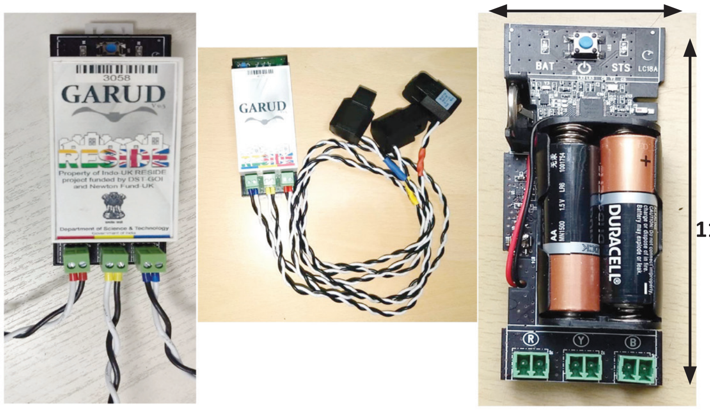

Figure 4 (left to right): Image of Garud, Garud connected to CTs and internal PCB of Garud

IV. Application of the Proposed Approach for Developing a Current Logger – Garud

This section describes the Garud current logger being developed using the proposed approach. It measures current, which can be used to approximate the energy consumed. *Table 1* summarizes the technical specifications of the current logger.

Table 1: Garud current logger specifications

Dimensions	11 x 4.5 x 3.5 cm
Range	0.1-100 Amps
Accuracy	1%
Resolution	24bit Delta-sigma
Memory	4MB
Radio power	-4dB
Transmission Range	Approximately 10 meters line-of-sight
Wireless Data Standard	Bluetooth Smart (Bluetooth Low Energy, Bluetooth 4.0)
Logging Rate	3 second
Data download modes	1 min averaged, 5 min averaged, 10 min averaged, 15 min averaged, half-hour averaged
Time Accuracy	3-5 min/year
Battery Type	2 user-replaceable AA 1.5V

The Garud current logger shown in *Figure 4* is connected to the line that is coming from the utility. For the basic operation of the device, the current transformers produce an output in proportion to the current flowing through the utility line, which is fed to the ADC. The ADC digitizes the analog value and sends the data to the microcontroller over I2C interface. The microcontroller samples the data every 3 seconds and averages the data for 1 min (20 samples). The microcontroller then saves the data into persistent memory, i.e., flash memory at every 40 min interval. The current logger connects to the mobile device over BLE interface. Here, the data is fetched by the microcontroller from the flash memory and pushed to the mobile device over BLE notification. These data values (sample is shown in *Figure 5*) are saved and processed over the cloud. The installed and pending list of homes, current values,

4C003D001D0051013D001D0054013D001D0062013D001D002B013
D001D008C013D004F00F5013D005A005D033D008A0017043D008B
0005043D008A00F3033D008B00EB033D008A00E3033D008A00DB0
33D008900D2033D008A00C2033D008A00C3033D008A00C0033D00
8A00BD033D008A00C1033D008A00C3033D008A00BE033D008A005
2033D008A005C023D008A0058023D008A005B023D008A0059023D
008A0058023D008A0057023D008A0054023D008A0056023D008A0
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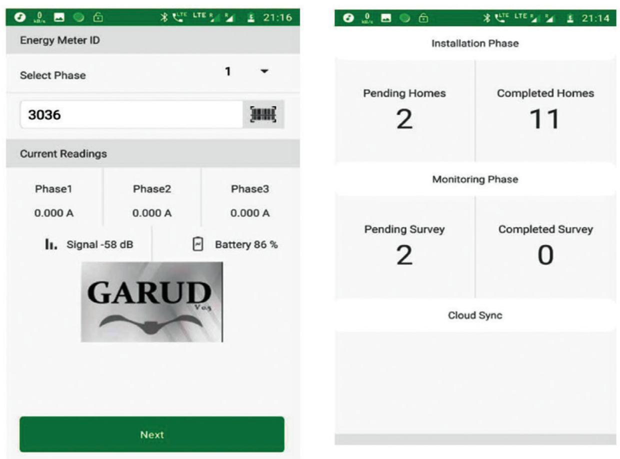

Figure 5 (top to bottom): Data sample sent from Garud to mobile, screenshots of the mobile application

Garud battery percentage, and signal strength are visible on the mobile application screen, as shown in *Figure 5*.

Since Garud is a new sensor, there was a need to pilot test it before deploying in the field. There were five tests performed to check various parameters of the device and the results show that the device works effectively in different conditions.

***TEST 1** – Signal strength and data download:* This test was performed to check whether household devices impact the signal strength and data download from Garud. The device was kept at different distances and with noise from different appliances, including a Wi-Fi router that emits RF signals. Observations show the logger is resistant to EMI and had minor signal strength deterioration when measured alongside the Wi-Fi router. Further, no faulty behaviour of the device was reported during the experiment and data logged without errors. *Figure 6* shows the test setup with 10 home appliances (including Wi-Fi router) connected to Garuds.

Figure 6: Setup with home appliances along with Garud and screen shot of signal strength

***TEST 2** – Battery life:* The objective of this test was to check Garud's battery performance and efficiency of the buck-boost regulator present in the device. The battery voltage of Garud was measured twice a day at an interval of 12 hours. The measurements were taken for one-month duration. Experimental results show that battery gets discharged at a higher rate when the battery level is between 3.1V and 3V, whereas discharge rate is low when battery < 2.9V. The graph in *Fgure 7(a)* shows the battery discharge curve for Garud. The buck regulator MAX17222 from Maxim Integrated was tested for efficiency with different voltages

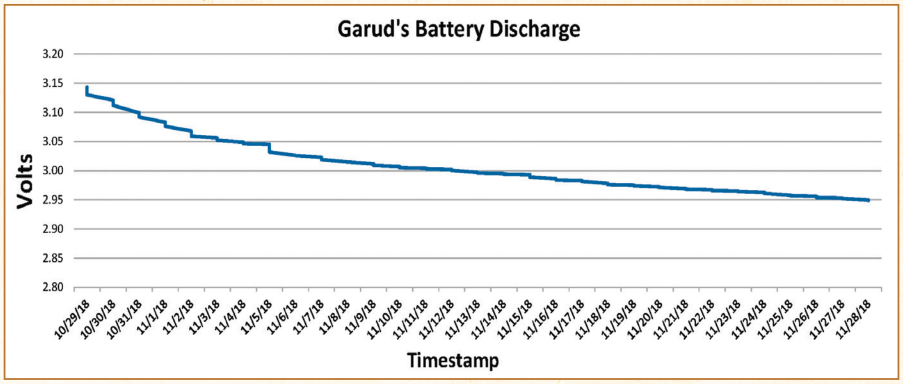

Figure 7(a): Voltage drop vs. timestamp for AA battery used in Garud

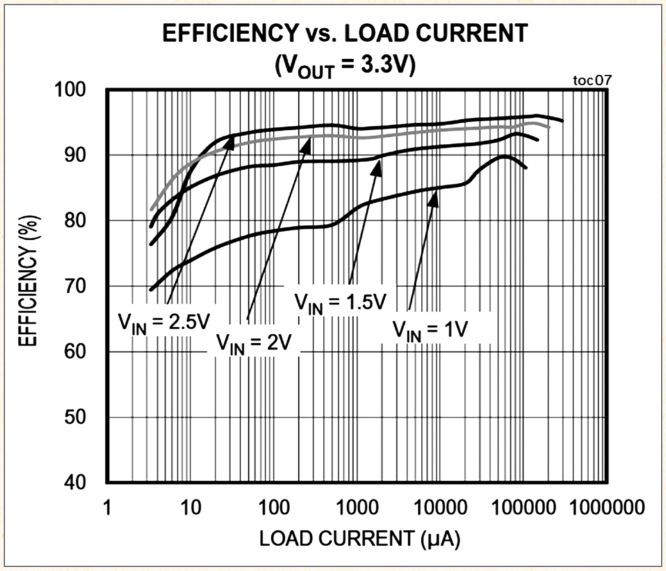

Figure 7 (b): Efficiency vs. load current for different input voltages [23]

for different load currents. Results show that the regulator works at 70% efficiency when the input battery voltage is > 3.1V, whereas at 95% when in the range of 1V and 2.8V, as shown in *Figure 7(b)*. By conducting Test 2 for battery life, the device is expected to work for at least 1 year with 2 AA batteries.

Table 2: Reference devices and their specifications

S. No.	Reference device	Model Number	Accuracy
1	Yokogawa	WT330	The basic accuracy for all input ranges is 0.1% rdg + 0.1% rng (50/60Hz) DC 0.1% rdg + 0.2% rng (0.2% + 0.2% for 40A)
2	WattNode	WNC-3Y-480-MB	Meter accuracy of 0.2% excluding CTs

***TEST 3** – Accuracy under varying loads:* This experiment tests the accuracy of Garud by comparing and calibrating it with Yokogawa meter [23] and a field meter (Watt Node) [24]. *Table 2* provides the specifications of reference meters. The experiment was performed by varying the load connected across Garud, WattNode, and Yokogawa (WT330). The current was varied from 100 mA to 12A to get a full-scale reading. *Figure 8* shows the scattered chart for the three-phase current measured from Yokogawa (WT330) and WattNode. Measured current for both devices for all three phases is accurate with R2 values of 0.9983, 0.9984, and 0.9984 for R, Y, B phases, respectively.

Figure 8 shows the chart between Yokogawa (WT330) and Garud. Garud loggers were calibrated on a wide range of currents across the CT. This method helps in calibration that needs to be performed on each CT and ADC channel of Garud. The calibration technique performed has satisfied the accuracy requirements.

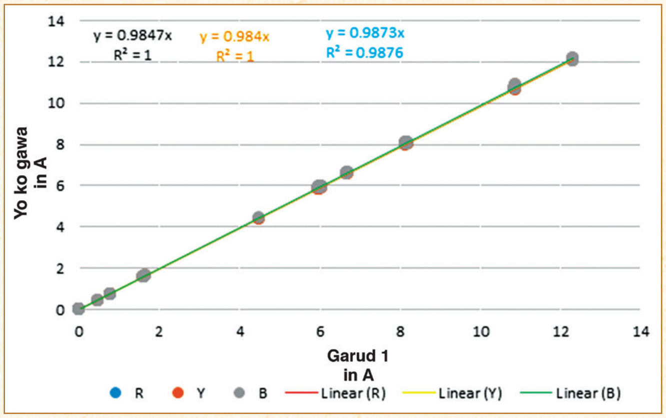

Figure 8: Correlation graph of Yokogawa (WT330) and Garud readings

TEST 4 – *Physical Strength:* Garud was tested for durability by dropping it from a height of 1.2m, 2.0m and 2.5m on a concrete floor in different orientations. After the drop test, the components were assembled again and tested for proper functioning. When dropped, we have observed that the device split into 3 pieces: PCB, the base of enclosure and top cover of the enclosure as shown in *Figure 9*. However, there was no visible damage to the device, internal cables, or the PCB and the enclosure. There was also no battery leakage, venting, or ruptures and the test unit normally operated after assembly.

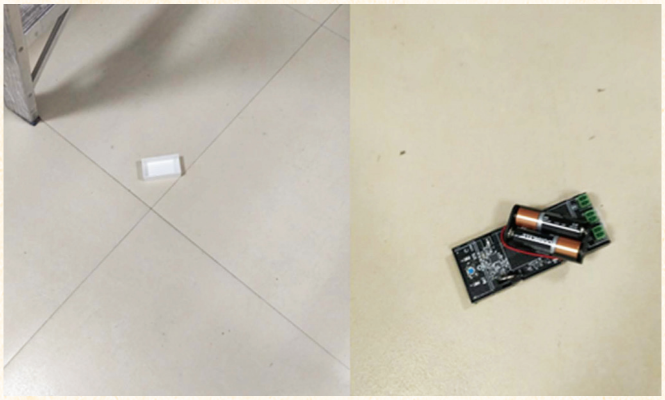

Figure 9: Parts of Garud after drop test

TEST 5 – *Connectivity with different smartphones for data collection:* The objective of Test 5 was to check the connectivity of Garud with different smartphones for data collection without loss of data packets. Five different mobile phones were tested to connect and download the data. All the mobile handsets were able to scan the devices and connect to them. The mobile phones had Android Operating System – API level 23.

V. Conclusion

The popularity of energy and IEQ monitoring in residential buildings has increased significantly in recent times, driven by the need to assess energy and environmental performance. Vendor-specific sensors and loggers available in the market use different mediums of communication, a variety of protocols and cloud platforms for communication and storage, making it difficult for researchers to use them for evaluating building performance. This paper has described an approach for the design, development and testing of a new sensor system, which uses open hardware, open software and standard protocols for data communication and storage. The solution proposed uses low-power components, BLE-based communication to transfer data from loggers to mobile phone and further transfer to the cloud using oneM2M protocol. Accessing data from the cloud storage to the applications for visualization and analysis uses the NGSI-LD protocol, thus enabling inter-operability between devices, applications, and cloud storage. Such a system will help researchers, auditors, and house owners assess building energy performance. The experiments conducted to test the wireless, low power, cost-efficient, mobile app-based data logger – Garud – proved to work effectively in different conditions for the parameters signal strength, battery life, accuracy, physical strength, and connectivity with different devices Since this system is part of a pilot study, it will be shared as an open framework only after testing it for durability and performance on a large scale.

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