An IoT-based bin level monitoring system for solid waste management

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Abstract
Improper disposal of solid waste that impacts human health and pollutes the environment, arising a need for successful and necessary collection of waste materials. However, most trash bins placed in cities can be seen overflowing due to traditional or inefficient waste management approaches. Therefore, a real-time remote monitoring system is needed to alert the level of garbage in bins to the relevant authority for immediate waste clearance. This paper presents the development and validation of a self-powered, simple connect, IoT solution to monitor the unfilled level of trash bins from a central monitoring station. The end sensor nodes of the developed IoT system are called Bin Level Monitoring Unit (BLMU) which are installed in every trash bin where the unfilled level needs to be monitored. Every BLMU measures the unfilled level of the trash bins and transmits it to a wireless access point unit (WAPU). Each WAPU receives the unfilled level data from several BLMUs and uploads it to the central server for storage and analysis. The waste collection authority can view and analyze the unfilled level of each bin using a smart graphical user interface. The following important experiments were carried out to validate the developed system: (1) the developed bin level monitoring system was tested by filling a trash bin with solid waste at various levels, and the corresponding unfilled level of the trash bin was monitored using the smart graphical user interface. (2) The life expectancy of the BLMU was evaluated as approximately 434 days. (3) The maximum transmission distance between a BLMU and a WAPU is 119 m. (4) The cost of a developed trash bin is 107 USD. Based on the results achieved, the developed trash bins can be suitable for smart cities.

Keywords Solid waste management · Internet of things · Smart city · Bin level monitoring

Introduction

The trend of urbanization is emerging worldwide. According to United Nation's population division 2014, 70 percentage of the population would be living in cities by 2050 [1]. Since more population moving to urban areas, city administrations across the globe are allocating more budgets for infrastructure [2]. The cities which are safe, sustainable economy, well-organized, contented, renewable energy, competent mobility, energy efficient and interactive are called as "smart cities" [3]. In smart cities, the key infrastructure can be designed by IoT systems, sensor networks, cameras, data centers, and so on, which allows the city authorities to provide essential services to the customers in an efficient manner. Also, smart cities use technology proficiently for transport management scheme, advanced health care services and develop robust reliable wireless communication networks to connect all businesses, people and things [4, 5]. One such essential service is solid waste management.

Solid wastes are related to materials produced by human activity, and the process is generally undertaken to reduce its effect on health and the environment of smart cities [6]. According to the world bank, the world cities generated 2.01 billion tons of solid waste add up to a footprint of 740 g per person in a day in the year 2016. Owing to rapid population growth and urbanization, the annual waste generation is expected to increase by 70 percentage

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from 2016 levels to 3.40 billion tons in 2050. Although under-developed countries over 90 percentage of waste is disposed in unregulated dumps or burned openly [7]. Improper handling of solid waste leads to serious health issues: contaminates local water bodies, air and land resources, causes climate change and marine plastic pollution, hinder climatic variation adaptation and, accelerate depletion of forests and mines [8]. In order to handle solid wastes effectively, trash bins are installed. On the other hand, improper handling of trash bins, leads to the following crucial problems.

– When the solid wastes are intended to be collected daily, in case if the trash bins are empty, it will be wastage of time, fuel, and manpower.
– When the solid wastes are intended to collect once in a week, there is a chance for the trash bins to run over and the solid wastes may spread around the area, causing illness to the public, and will pollute the surrounding.

Deployment of solid waste bin level monitoring system resolves the aforementioned crucial problems. Most of the existing bin level monitoring systems use Radio Frequency Identification (RFID) technology [8–14]. Every trash bin in the bin level monitoring system is mounted with a RFID tag. The truck which is used to collect waste from the trash bins is mounted with a black box which consists of a RFID reader, a camera, and a GSM module. A worker is responsible to open the lid of each bin and adjust the camera to point out to every trash bin to acquire images. The camera used in this system is a low-resolution camera that can cover 6 m^2 area around a bin. Once the camera is pointed over the bin, it records images and sends them to the remote monitoring station through GSM network to find the trash bin level. Then, the worker collects the bin and dumps the waste into the truck. Once the images are received in the control room, using image processing techniques, the level of each bin is measured. However, a lot of human intervention takes place in RFID-based bin level monitoring system, and it does not resolve the critical problems of handling solid wastes. Also, the RFID fails to predict waste level efficiently because of the proximity and orientation issues. Again, it is not suitable for non-reachable places such as mountains, rustic areas or deep forests.

As a result, to overcome the issues of RFID technology, Internet of Things (IoT) and Wireless Sensor Networks (WSNs) must be used. The main features of IoT and WSN includes: ability to cope with node breakdown, mobility of nodes, heterogeneity of nodes, scalability to large scale deployment, ability to withstand the harsh ecological conditions and the ease of use [15, 16]. The mentioned features ensure a wide range of remote monitoring systems, such as energy flow monitoring in smart grids [17], air quality monitoring [18], toxic gas monitoring [19], continuous steel casting [20], health care [21] and so on [22, 23].

Waste management is another important application of IoT and WSN. Sensor-based smart bin without a radio device is presented in [24], which is impossible for remote monitoring and also the implementation cost is very high. A WSN-based architecture to monitor the bin level is presented in [25]. This paper uses ArgosD sensor nodes that consist of a CC2420 RF transceivers, a MSP430F1611 microcontroller and a sensor. The implementation of the monitoring system is not clearly mentioned and none of the network metrics or metrics related to the hardware have been evaluated. The monitoring software shows the level of each bin but fails to show as organizational view. To overcome the above said issues, a new system was developed to monitor the unfilled level of each bin [26]. This bin level monitoring system consists of a wireless monitoring unit, a wireless access point unit, and a central monitoring station which uses a monitoring application. The wireless monitoring unit is a combination of an ultra-sonic sensor, a MSP430 microcontroller, and a radio namely CC2500 which uses simpliciTI network protocol. The ultrasonic sensor is directly coupled to the digital input/output (I/O) lines of the microcontroller, measures the unfilled level of the bin and transmits data to the wireless access point unit, wirelessly at a frequency of 2.4 GHz. The wireless access point unit receives data from all the wireless monitoring units and sends data using universal asynchronous receiver / transmitter, connected to the central monitoring station. The main disadvantages of this bin level monitoring system are, the sensor nodes run with battery power would last long about 28 days for 1 A×h batteries and 288 days 12 h, 55 min for 10.4 A×h power bank. Also, a personal computer or a personal digital assistant is needed to send unfilled value to remote monitoring station. To overcome the above said issues, [27] proposed a WSN framework with solar energy harvesting facility. This bin level remote monitoring system with solar energy harvesting facility reduces the costs of a personal computer or a personal digital assistant. A LoRaWAN wireless technology-based smart waste collection system is proposed in [28], where the data can be transmitted to a long distance with low power and low data rate.

The existing bin level monitoring systems such as RFID, Zigbee, Bluetooth, 6LoWPAN, SimpliciTI, LoRaWAN, Sigfox, and DASH7, requires an additional infrastructure to implement in smart cities which escalates the implementation cost. This paper presents the development and validation of a self-powered, low-cost, smart connect, IoT-based solid waste management system (IoT-SWM). The other features of the proposed system are, over-charging and over-discharging battery protection, battery condition indicator, smart graphical user interface to monitor the bin level and to locate the trash bin. Smart connect Wi-Fi module enables

the trash bin to connect with the existing Wi-Fi networks which reduces the additional infrastructure requirement to implement in smart cities.

The rest of the paper is organized as follows: Sect. 2 describes the design of the proposed IoT system; Sect. 3 shows the results and discussion; Sect. 4 concludes the paper.

Design of the IoT-SWM system

The architecture of the proposed IoT-SWM system, design of Bin Level Monitoring Unit (BLMU), Wireless Access Point Unit (WAPU) and the smart graphical user interface are described in this section.

Network architecture of the proposed IoT-SWM system

IoT-SWM system employs WLAN architecture in which the BLMUs are connected to the IoT-SWM server in stars of star topology. The proposed IoT-SWM system mainly consists of two modules namely bin level monitoring unit (BLMU) and central monitoring station which is shown in Fig. 1. The trash bins which are present in every region are equipped with a BLMU, which measures the unfilled level of bins and

sends to a WAPU present in the same region at a frequency of 2.4 GHz. The WAPU receives the unfilled level data from all the BLMUs, and forwards to the remote monitoring station for long time storage and analysis.

Design of the bin level monitoring unit (BLMU)

The BLMU mainly consists of an ultrasonic sensor, a single-chip micro controller cum network processor and a power management unit. The schematic diagram of the BLMU is shown in Fig. 2, and the photograph of the populated printed circuit board, installation of an ultrasonic sensor, and other parts are portrayed in Fig. 3. BLMU uses a light weight, small size, commercially available MB1010 LV-Maxsonar-EZ1 ultrasonic sensor to measure the unfilled level of a trash bin. MB1010 LV-Maxsonar-EZ1 can detect solid wastes within the wide range between 0 cm and 6.45 m without any dead zone for the sensing range. The ultrasonic sensor is powered with a DC voltage of 5 V by a dc–dc converter and the sensor is capable of providing three types of output simultaneously such as analog voltage, pulse width, and RS232 serial. The ultrasonic sensor was interfaced with the smart connect module (ATSAMW25) through a 12-bit analog to digital converter (ADC).

ATSAMW25 system on chip is a commercially available smart connect WiFi module, integrated with 802.11 IP stack.
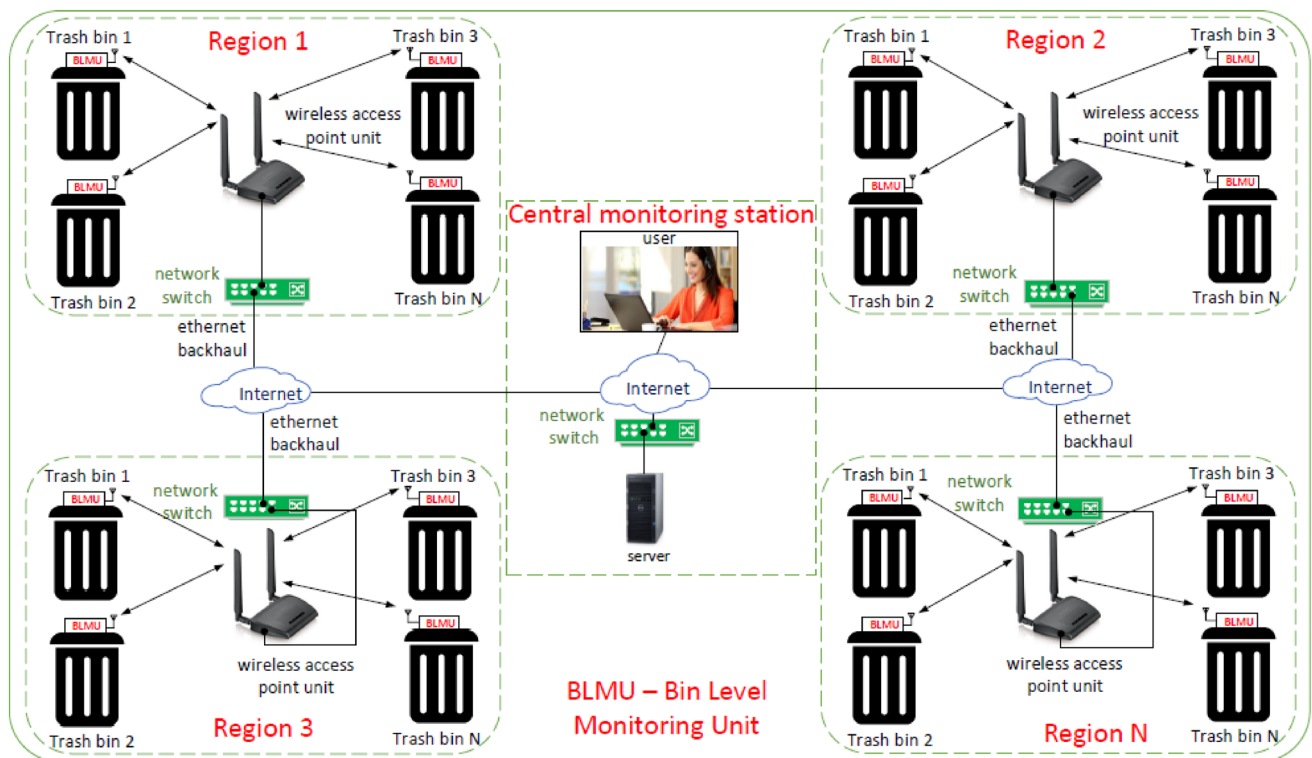

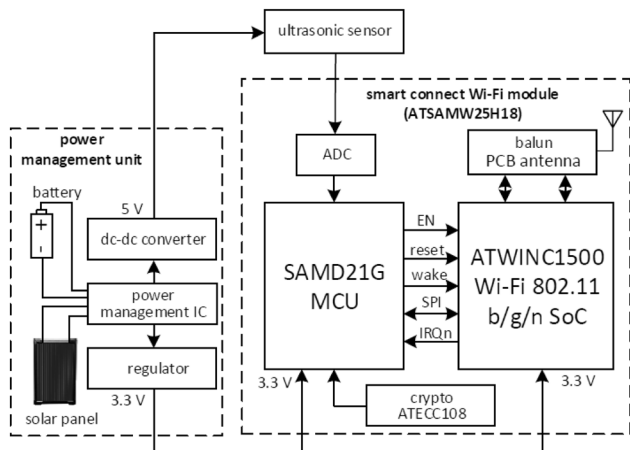**Fig. 1** Network architecture of the proposed IoT-SWM system

Fig. 2 Schematic diagram of the bin level monitoring unit

It consists of a microcontroller based on ARM cortex M0 and a Wi-Fi network processor ATWINC1500. It has an on-chip memory management engine to reduce the host computer load. It is equipped with an 8 Mb internal flash memory for over the air (OTA) firmware up-gradation. Transport Layer Security (TLS), Secure Socket Layer (SSL) protocols are incorporated to establish secure network connectivity. It also has additional network services, such as Dynamic Host Configuration Protocol (DHCP), Domain Name System (DNS), User Datagram Protocol (UDP), Hypertext Transfer Protocol (HTTP), and secure Hypertext Transfer Protocol Secure (HTTPS). It has 12-bit ADC with 14 channels and a 10-bit DAC. Smart connect Wi-Fi module is operated at a DC voltage of 3.3 V by a low dropout (LDO) regulator.

A working flow diagram of the BLMU is shown in Fig. 4. Once the system is initialized, the microcontroller switched into active mode and enables the dc–dc converter to power up the sensor in reading mode. The microcontroller reads

Fig. 3 Photograph of the developed smart trash bin. **a** Populated printed circuit board and other parts of the BLMU. **b** Installation of an ultrasonic sensor. **c** Full view of the smart trash bin
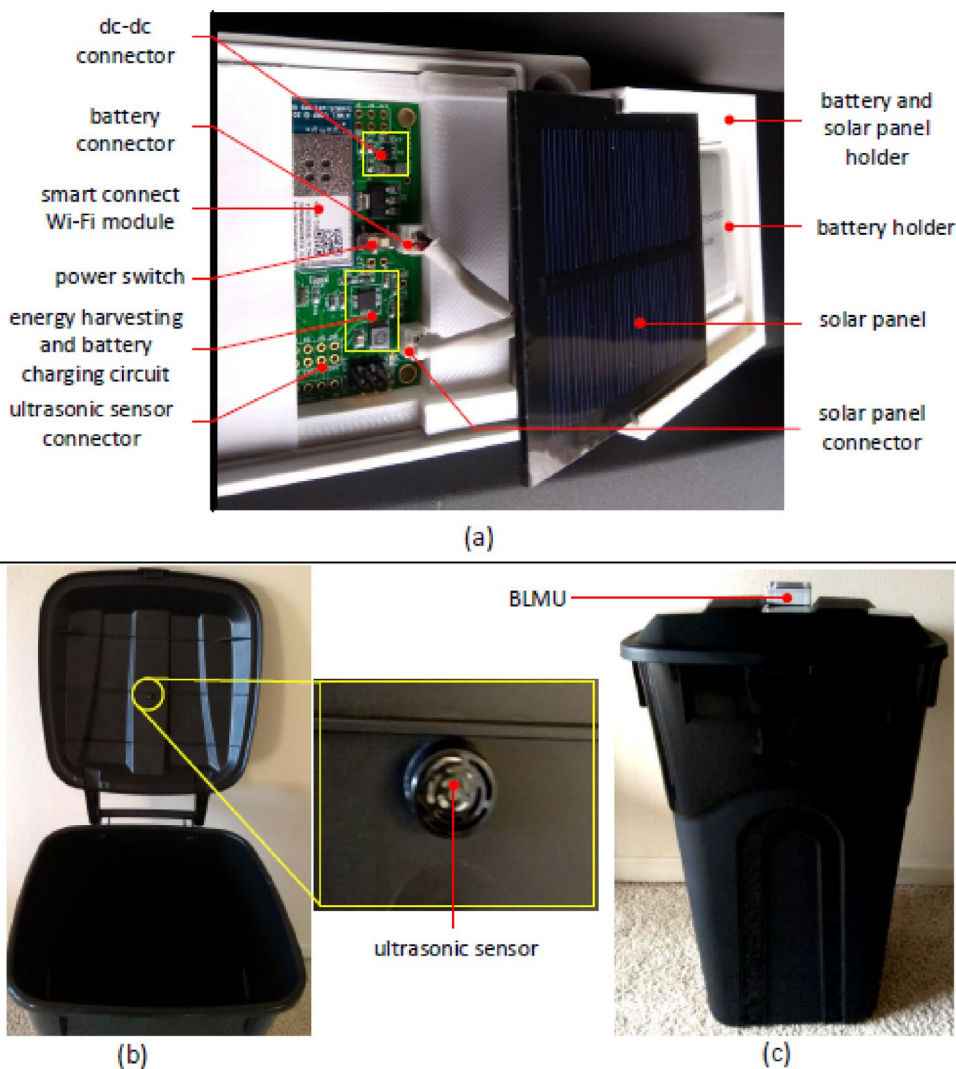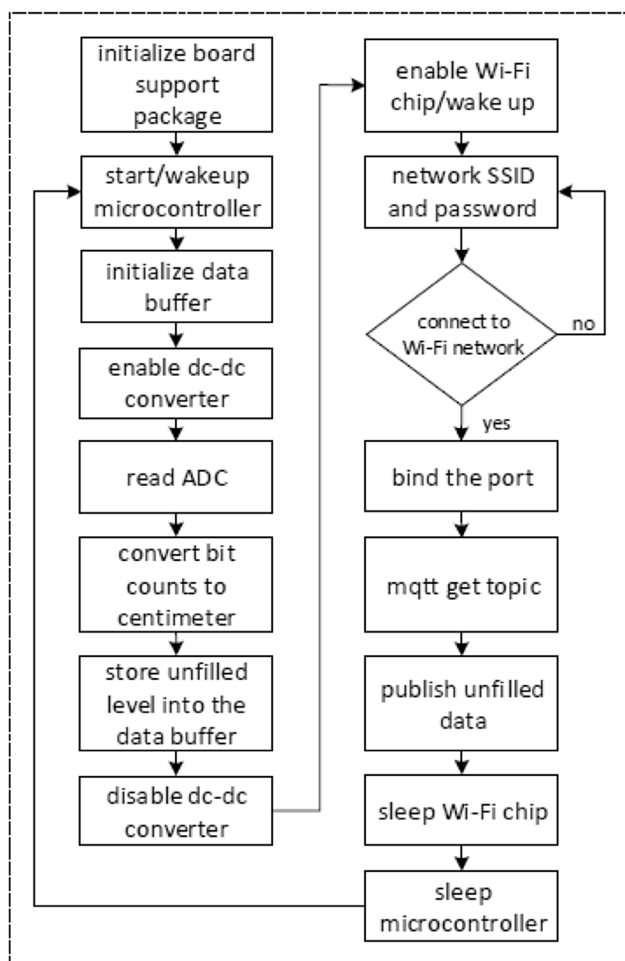
Fig. 4 Flow diagram showing the firmware employed in the BLMU

the sensor data through its ADC pin and converts it into centimeters and stores in the data buffer. After completing the reading operation, the microcontroller disables the dc–dc converter to save power and enable the Wi-Fi chip to connect to the IP network through DHCP. Once the network connection is established, BLMU publishes the unfilled data to the server through the MQTT broker. When the data are uploaded into the server, the Wi-Fi chip and the microcontroller goes to sleep mode. The same process will be repeated for every 5 min.

IoT-SWM communication protocol

IoT-SWM system uses highly efficient Message Queuing Telemetry Transport (MQTT) protocol to transport the unfilled level data from every BLMU to the server. MQTT protocol has two types of network entities, such as message broker and clients. In the proposed architecture, BLMUs and the bin level monitoring server are the clients, which are publishing and subscribing the data from the

MQTT broker. The BLMUs are the publishers that are sending the data to the topic (unfilled level of the trash bins) defined in the MQTT broker and the bin level monitoring server is the subscriber which receives data from the MQTT broker. The lightweight, low power consumption, fast data transmission and easiness in implementation are the reasons to opt this protocol for the design of the IoT-SWM.

Wireless access point unit (WAPU)

Smart cities are equipped with wireless access point units to provide data connection to users. For the experimental purpose, the WAPU used in this bin level monitoring system is a TP-Link TL-MR3020 wireless router. The data transmission speed is up to 150 Mbps. It supports IEEE 802.11b/g/n wireless standards. In addition, it is secured by WEP/WPA security schemes.

Power management unit

A power management unit comprises of an energy harvesting and battery charging circuit, a DC to DC converter and a low-dropout regulator. In addition, a Li-Ion battery of 2500 mAh capacity is employed to power up the BLMU. Likewise, a solar panel is used to charge the battery which is a monocrystalline silicon solar cells which has the open circuit voltage of 4.6 V, short circuit current of 105 mA and the maximum power of 0.4 W at 1000 W/m2 and 25 °C. The energy harvesting and battery charging circuit is designed by using BQ25505 chip which is an ultra-low power with high efficiency DC–DC boost charger. It is specially designed by Texas Instruments to efficiently extract the power generated from the solar panel and to store energy in the battery. BQ25505 can harvest energy continuously from a solar panel as low as 100 mV. The features of BQ25505 are ultra-low quotient current consumption of 325 nA, input voltage regulation which prevents the collapse of solar cell, battery good flag, integrated maximum power point tracking from the solar panel. To prevent the Li-ion battery from being deeply discharged and damaged, and to prevent from being exposed to excessive charging, the chip is programmed as 3 V as under-voltage threshold and 4.2 V as over-voltage threshold. A dc − dc converter MCP16252T is used to boost the output voltage from the energy harvesting and charging circuit to 5 V to power up the ultrasonic sensor. MCP16252T has the typical efficiency of 96 percentage, low output quiescent current of 4 μA, and automatic PFM/PWM operation. The low-dropout regulator MCP1825S is used to regulate the voltage level at 3.3 V to power up the smart connect Wi-Fi module.
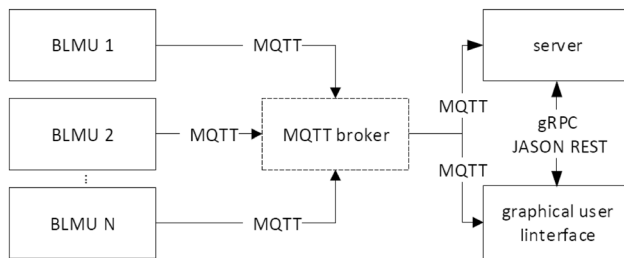
Fig. 5 Software architecture of the IoT-SWM server and the graphical user interface

Table 1 Threshold level used in the smart graphical user interface

Unfilled level (Cm)	Filled area color	Status
Unfilled level = 82.5	Green	Empty
Unfilled level > 70	Green	Lightly filled
30 < unfilled level < 70	Orange	Partially filled
Unfilled level < 30	Red	Almost full

Bin level monitoring server, and graphical user interface

The hardware configuration of the IoT-SWM server is i7 processor (eighth generation), 500 GB hard drive and 8 GB RAM, with Ubuntu 18.04 LTS operating system. The IoT-SWM server package consists of Eclipse Mosquitto, Redis, PostgreSQL, smart graphical user interface, and the software server architecture is shown in Fig. 5. Eclipse Mosquitto is a light weight open source message broker which implements MQTT protocol. Redis is an in-memory database which stores transient bin level data and PostgreSQL is used to store the unfilled level data for long time. The smart graphical user interface is developed using C Sharp programming language based on .NET architecture. The .NET core 3.0 integrates gRPC framework which is a lightweight and highly performant RPC framework to push messages in real time without polling. Once the bin level data are decoded and systematically stored, the created graphical representation of the main window, all region icons and all the bin icons are graphically mapped according to the BLMU measurement. To identify the bin level in a quick glance, different color codes are used for different levels.

Results and discussion

Testing of the developed system

An experiment was carried out to validate the developed IoT-SWM system. The height (maximum unfilled level) of the trash bin used was 82.5 cm and the firmware of BLMU is programmed to send the unfilled data for every 5 min. Considering the BLMU measurement and the maximum unfilled level of the trash bins, the smart graphical user interface maps each trash bin to a color code. The threshold levels for the trash bin will differ depending upon the height (maximum unfilled level) of the trash bin, and the threshold levels used in the experimental system are presented in Table 1.

Figure 6 shows the screen shot of the developed smart graphical user interface used to identify the exact bin level and to identify the location of the bin. Every 2 min, the smart graphical user interface updates the unfilled level values of every trash bin present in the IoT-SWM system. The main icon (main window) of the smart graphical user interface is a progressive bar, which is synchronized to all the BLMUs present in the IoT-SWM system. The color code of the main icon is mapped to the lowest unfilled value of the trash bins in the IoT-SWM system. When the user clicks on the main icon, the smart graphical user interface opens the region icons. The region icon also serves as a progressive bar in which the status depends on the unfilled value of BLMUs present in that particular region. The color codes of the region icons are mapped to the lowest unfilled level value of the trash bins present in that particular region.

When the user clicks the region icon, the smart graphical user interface displays all the trash bins present in that particular region. The trash bin icons also a progressive bar in which the status depends on the sensor value mapped to the trash bin. From Fig. 6, it is observed that the main icon color is red since the unfilled value of trash bin 1 is 11.2 cm which is less than 20 cm (threshold value) draws immediate attention to the user stating that some trash bins in the IoT-SWM system is almost full. The region icons are displaying different colors: Region 1 is red in color since the unfilled value of trash bin 1 is 11.2 cm. Similarly, Regions 2 and 3 are in orange color because the unfilled level of the trash bins in these regions lies between 20 and 70 cm. Region 4 is green in color since the unfilled level of all the trash bins in that particular region are greater than 70 cm. If the user clicks on the particular trash bin, it displays the exact decimal value. In this way, the user can monitor the unfilled level of each trash bin from a central monitoring station with the help of the smart graphical user interface.

Expected current consumption of the BLMU

The current consumption of the BLMU is shown in Fig. 7, which shows the active current and sleep current consumption of an ultrasonic sensor, a smart-connect Wi-Fi module, a dc–dc converter, and an LDO.

Sleep current contribution of the BLMU is

$$I_{\text{BLMU}}^{s} = \left(I_{\text{LDO}} + I_{\text{DC - DC}}^{s} + I_{\text{controller}}^{s} + I_{\text{radio device}}^{s} \right) \times \left(T - T_{\text{controller}}^{a} \right) \tag{1}$$
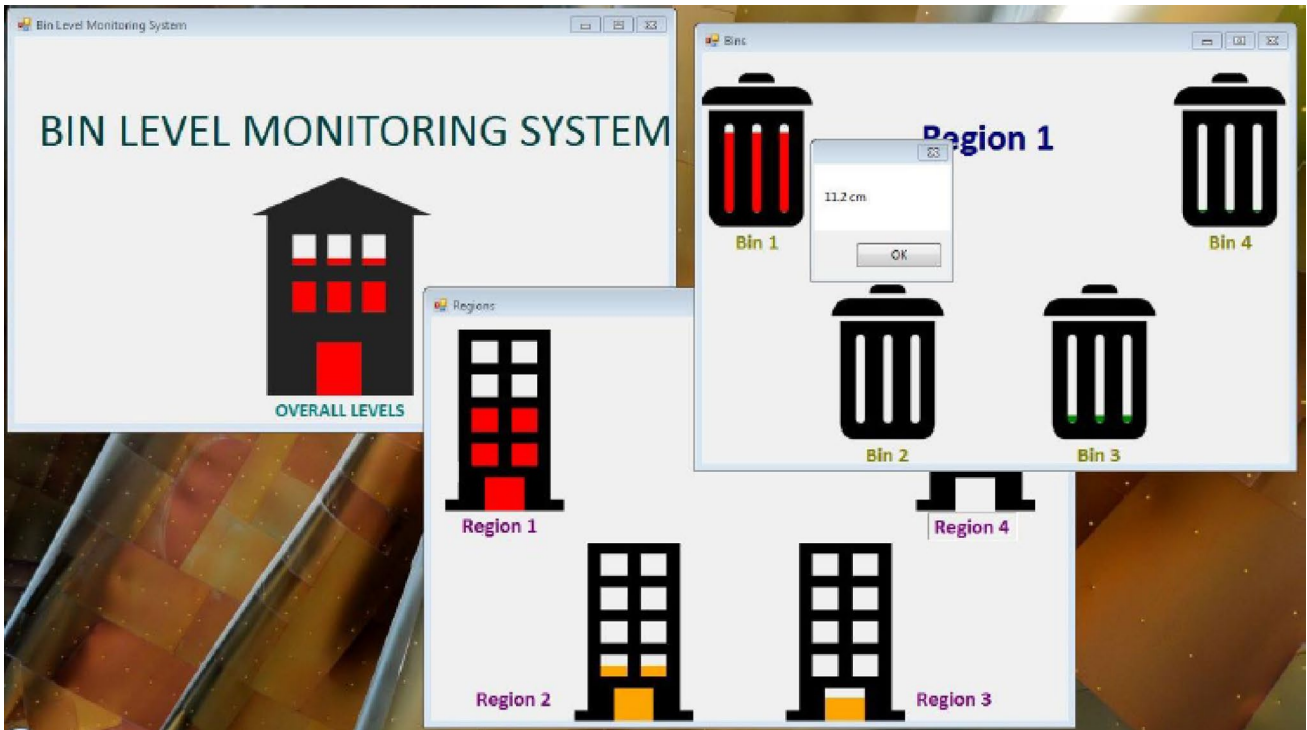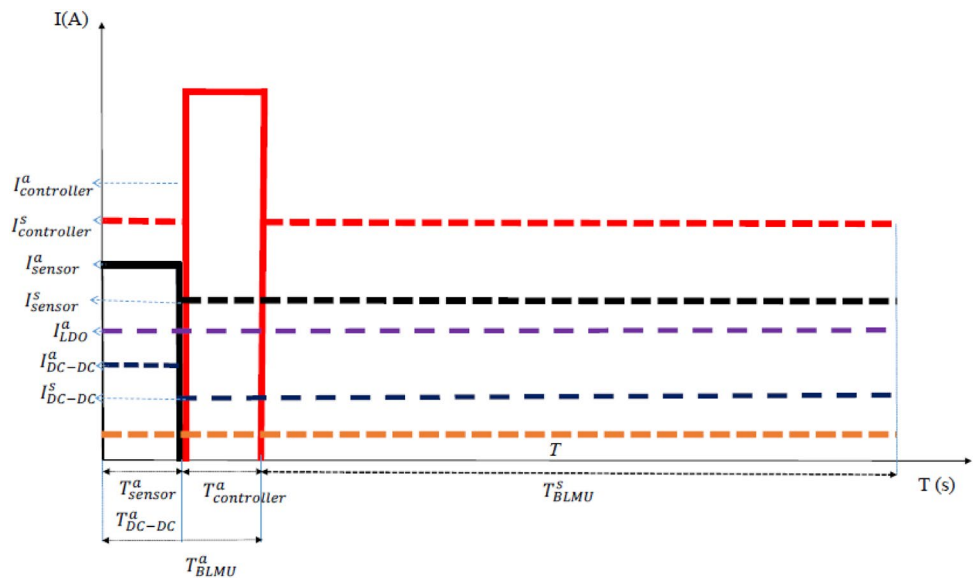
Fig. 6 Smart graphical user interface displaying the status of trash bins

Fig. 7 Description of current consumption of the BLMU

$$= (120 \times 10^{-6}A + 1 \times 10^{-6}A$$
$$+ 70 \times 10^{-6}A + 4 \times 10^{-3}A) \times (300s - 0.750s) \qquad (2)$$

$$= 0.05835A \times s \qquad (3)$$

where, I_{LDO}, current consumption of the LDO; $I_{DC\text{-}DC}^s$, sleep current of the dc − dc converter; $I_{controller}^s$, current consumption of the host microcontroller in sleep mode; $I_{radio\ device}^s$, current consumption of the Wi-Fi network processor in sleep mode, T, total transmission period; $T_{controller}^a$, active time period of the host microcontroller.

Active current contribution of the BLMU is

$$I^{\text{a}}_{\text{BLMU}} = \left(I^{\text{a}}_{\text{sensor}} \times \text{time executed} + I_{\text{LDO}} \times \text{time executed}\right.$$
$$+ I^{\text{a}}_{\text{DC - DC}} \times \text{time executed}$$
$$+ I^{\text{a}}_{\text{controller}} \times \text{time executed}$$
$$\left. + I^{\text{a}}_{\text{radio device}} \times \text{time executed}\right)$$

(4)

$$= (0.0001A \times s + 0.000084A \times s + 0.01125A \times s$$
$$+ 0.002352A \times s + 0.0001376A \times s$$
$$= 0.013923A \times s$$

(5)

where, $I^{\text{a}}_{\text{sensor}}$—active current consumption of the ultrasonic sensor, $I^{\text{a}}_{\text{DC - DC}}$—active current consumption of the dc − dc converter, $I^{\text{a}}_{\text{controller}}$, active current consumption of the host microcontroller; $I^{\text{a}}_{\text{radio device}}$, active current consumption of the Wi-Fi network processor.

Expected average current consumption of the BLMU

$$I = \frac{I^{\text{s}}_{\text{BLMU}} + I^{\text{a}}_{\text{BLMU}}}{T} = \frac{0.05835A \times s + 0.013923A \times s}{300s} = 0.24 \text{ mA}$$

(6)

Life expectancy of the BLMU

The life expectancy of the BLMU was evaluated under the hypothetical condition, in which the voltage of the battery is ideal until its capacity is exhausted. Assume a typical battery with a capacity of 2500 mA×h and the life expectancy is calculated as follows.

$$T_{\text{days}} = \frac{Q_{\text{Battery}}}{I}$$

(7)

$$\cong 434 \text{ days}$$

(8)

where, T_{days} is the total days of operation of the BLMU, Q_{Battery} is the capacity of the battery used, and I is the expected current consumption of the BLMU.

Evaluation of maximum power generated by the solar panel and battery charging time

In order to evaluate the maximum power harvested by the solar panel, an experiment has been carried out in an open space (40.429600, -86.911000). The solar irradiation was measured as 977 W/m^2 by a solar power meter and the corresponding open circuit voltage (V), short circuit current (mA) of the solar panel was recorded using a source meter. The VI characteristics of the solar panel used in the bin level monitoring system is plotted in Fig. 8. From the figure, it is found that the maximum power generated by the solar panel is 386.1272mW. where, $V = 4.15$ and $I = 92.819$.
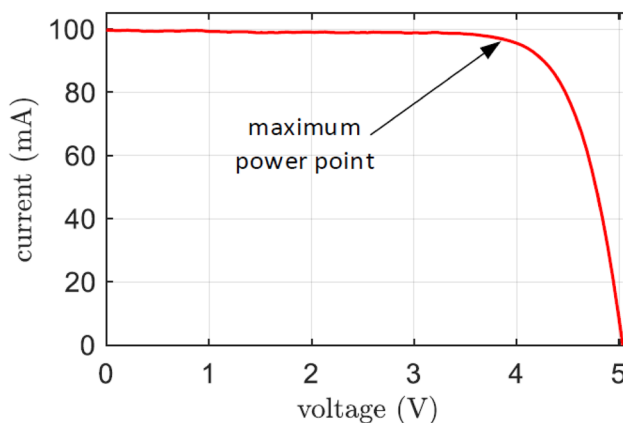
The battery charging time is calculated as follows

Fig. 8 Measured VI characteristics of the solar panel at the solar irradiance of 977 W/m^2
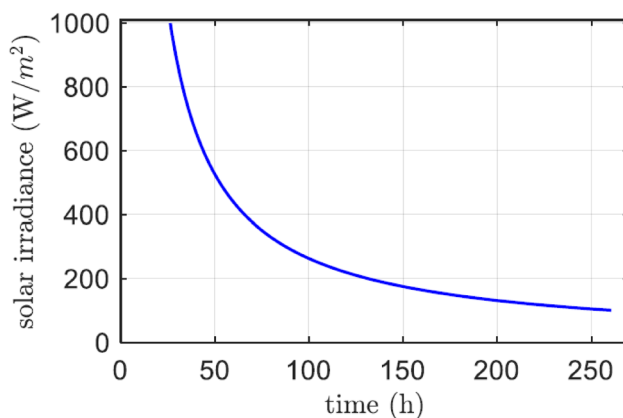

Fig. 9 Calculated battery charging time in accordance with the measured maximum power point of the solar panel

$$T_{\text{bc}} = \frac{B_{\text{c}}}{I_{\text{sp}}}$$

(9)

where, T_{bc} is the battery charging time, B_{c} is the capacity of the battery used (2500 mAh) and I_{sp} is the current generated by the solar panel. The power generated by the solar panel is directly proportional to the solar irradiance, and the battery charging time is calculated as 26 h 56 min for the solar irradiance of 977 W/m^2 as shown in Fig. 9. Once the battery is completely charged (26 h 56 min for the solar irradiance of 977 W/m^2), according to the life expectancy calculation of the BLMU, the operation of the BLMU can last long for 434 days. From this study, it is found that the unfilled level of the trash bins can be monitored without any interruption even during rainy days.

Maximum distance data transmission between a BLMU and a WAPU

To evaluate the movement of bins in an environment, an experiment was carried out in an open space (line of sight propagation mode). To evaluate maximum distance of data communication between a BLMU and a WAPU, WAPU is kept immovable and the BLMU is moved at various distances. The BLMU is programmed to transmit 8000 packets to the WAPU at various distances and the corresponding packet loss rate was evaluated as follows.

$$\text{PLR} = \frac{T_{\text{PL}}}{T_{\text{PR}}} \tag{10}$$

where, T_{PL} is the total number of packets lost and T_{PR} is the total number of packets delivered successfully.

The packet loss rate with respect to distance is shown in Fig. 10. From the figure, it is observed that the packet loss rate is less than 2 percentage for the distance less than 119 m. From this experiment, it is found that the precise unfilled level of trash bins can be monitored from the remote monitoring station by keeping the BLMU at a distance less than 119 m (line of sight) from the WAPU without any practical failure in the signal. The surplus distance with acceptable packet loss rate needs additional installation of WAPU results in the movement of trash bins in larger environment.

Cost of the developed trash bin

The cost of each item present in the developed trash bin is listed in Table 2. From the table, it is noted that the total cost of the developed bin is USD 107. Moreover, a cost comparison between the developed trash bin and an existing trash
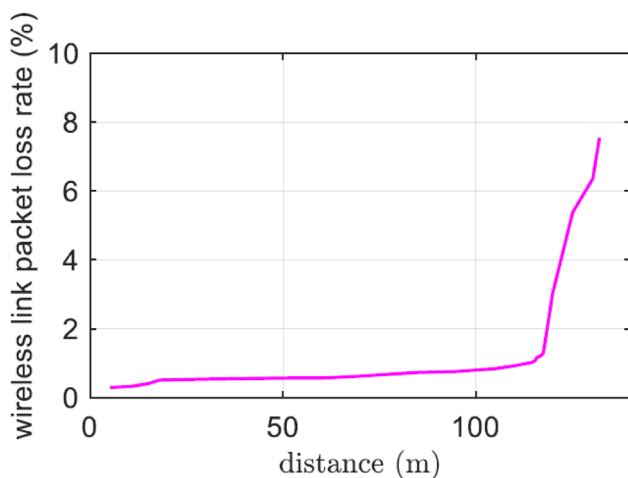
Table 2 Unit cost of the developed trash bin

Items	Cost in USD
Trash bin	$17
Ultrasonic sensor	$24.95
Wi-Fi module	$11.7
Energy harvesting chip	$3.77
DC–DC converter	$0.61
LDO	$0.51
Printed circuit board	$7.11
Battery	$14.95
Solar panel	$11.34
Resistors, capacitors, inductors and connectors	$4.5
Enclosure	$10.7
Total cost	$107.14

bin presented in [24] is shown in Fig. 11. To summarize, the cost of the developed trash bin is highly favorable with the cost of the existing trash bin, which costs around USD 560.

Conclusion

Self-powered, smart connect, IoT system for solid waste management was developed and presented in this paper. Three significant experiments were carried out. Firstly, the current consumption, battery charging time was estimated to find the life expectancy of the BLMU. From the experiment, it is found that the battery charge will last long for 434 days. Even in the worst cases like rainy days, the unfilled level of bins can be monitored perfectly without any interruption. Secondly, the precise unfilled level of bins can be monitored from the remote monitoring station by keeping BLMU at a distance less than 119 m from the
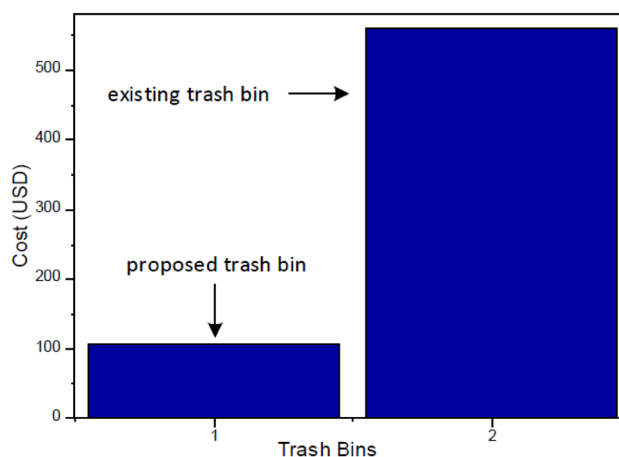

Fig. 10 Measured maximum distance wireless link data transmission between a BLMU and a WAPU

Fig. 11 Cost comparison between the proposed trash bin and an existing trash bin presented in [24]

WAPU without any practical failure in the signal. Thirdly, the implementation cost has been compared with an existing bin.

Future work in the area of IoT-based bin level monitoring system includes: integration of a GPS module into the BLMU to locate the trash bins; integration of a route optimization algorithm into the graphical user interface to evaluate the shortest route for trucks to collect the solid waste for disposal.

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