A LoRaWAN IoT enabled Trash Bin Level Monitoring System

S.R. Jino Ramson, *Member, IEEE,* S. Vishnu, A. Alfred Kirubaraj, Theodoros Anagnostopoulos and Adnan M. Abu-Mahfouz, *Senior Member, IEEE.*

***Abstract*—Municipal Solid Waste Management (MSWM) remains a major problem in urban areas, leading to serious health and environmental issues. Consequently, trash bins are placed in many places to handle municipal solid waste. These bins can overflow, spreading around the area, polluting the environment and causing inconvenience to the public. Therefore, there is a need for a real-time remote monitoring system that alerts the level of garbage in the trash bins to a municipality or a waste management company. To manage municipal solid waste efficiently, this paper presents the development and validation of a self-powered, LoRaWAN IoT enabled Trash Bin Level Monitoring System (IoT-TBLMS). The end nodes of the proposed IoT system are called Trash Bin Level Measurement Unit (TBLMU) and are installed in each trash bin where the status needs to be monitored. TBLMU measures the unfilled level and geographical location of a trash bin, processes the data and transmits to a LoRaWAN gateway at a frequency of 915 MHz. A LoRaWAN gateway serves as a concentrator for the TBLMUs and relays data between a TBLMU and an IoT-Trash Bin Level Monitoring (IoT-TBLM) server. The users can view and analyze the status of every bin and its geolocation by using a smart graphical user interface. The accuracy of the developed system, wireless range between a TBLMU and a LoRaWAN gateway, average current consumption and life expectancy of the TBLMU, battery charging time, and the cost were studied and are reported here.**

***Index Terms*—Internet of Things, LoRaWAN, real-time systems, sensor systems, remote monitoring, solid waste management, trash bin, solar-powered.**

I. Introduction

MUNICIPAL SOLID WASTE (MSW), more commonly known as trash or garbage, is a primary potential source of pollution [1]. However, it is an inevitable by-product of human activity [2]. Municipal Solid Waste Management (MSWM) remains as a major problem in urban areas, leading to serious health and environmental issues [3]. According to the survey performed by the urban development & local government unit of the World Bank, around 1.3 billion tons of solid waste are generated in world cities every year. In 2025, this amount is expected to grow to 2.2 billion tons [4].

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In order to manage solid waste efficiently, trash bins are installed in many spots by building managers, municipality or waste management companies. Certainly, the municipality or the solid waste management companies operate trucks to collect solid waste on daily basis. If the trash bins are not filled, then there is a waste of fuel and manpower. If the solid waste is scheduled to be collected once a week, trash bins may overflow, spreading waste around the area, polluting the environment and causing illness to the public. Therefore, there is a need for a real-time remote monitoring system that can alert the municipality or the waste management company about the level of garbage in the trash bins.

The technological developments in the sensor design, advancement in communication protocols and remote monitoring methods can provide effective solutions for the real-time monitoring of trash bins in urban areas. In [5]–[7], RFID based systems for trash bin level monitoring are presented. These systems consist of cameras with GIS (Geographic Information System) installed on the trucks to measure the garbage level of nearby bins. The possibility of unread tags, ghost tags and the need for image processing algorithms to extract the level of bins are the drawbacks of these systems. However, Wireless Sensor Network (WSN) based bin level monitoring systems overcome the drawbacks of RFID technology [8].

A wireless sensor network based trash bin level monitoring system is presented in [9]. This paper uses ArgosD sensor node which consist of a CC2420 RF transceiver and a MSP430F1611 micro-controller. A graphical user interface was designed to show the filled level of individual bins, but lags to show an organizational view of garbage bin levels either in region wise or cluster wise. However, no practical results were provided. A sensor based smart bin is presented in [10]. The developed smart bin uses multiple sensors to measure the lid status, garbage level and weight of the trash bin. Although, the developed smart bin is not designed to connect over a wireless network. Also, the implementation cost of the trash bin is expensive (USD 560 per trash bin).

To overcome the constraints of the aforementioned systems, a real-time WSN-based bin level monitoring system is presented in [11] and [12]. These systems consist of sensor nodes installed in the trash bins to measure the level of garbage and transmit to an access point. An access point collects data from the sensor nodes and sends it to a central monitoring station via a Universal Asynchronous Receiver Transmitter (UART). A low power, network protocol called SimpliciTI were used for wireless communication. In addition, the graphical user interface shows an organizational view of all the bins in

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location wise to easily identify the garbage level and the location of a trash bin. However, it costs a personal computer or a personal digital assistant to send the data to a remote location.

The limitations found in the above literature can be overcome by adopting Internet of Things (IoT) paradigm towards the design of a smart bin level monitoring system. IoT paves the way for creating pervasively connected infrastructures to support innovative services and promises better flexibility and efficiency. Such advantages are attractive not only for consumer applications, but also for the industrial domain [13]. Several IoT based remote monitoring systems have been employed in various fields such as environmental monitoring [14], temperature monitoring for electrical substations [15], pain monitoring system [16], continuous athlete monitoring in challenging cycling environments [17], infrastructure monitoring [18], rodenticide depletion monitoring [19], and so on.

Solid waste management is one of the key applications of IoT. Few approaches are thereby incorporating IoT in the design of trash bin level monitoring systems are reported in [20], [21]. The end sensor nodes of these system were equipped with a Wi-Fi module to upload the bin level data to a server. In [20], a RFID tag was installed in a trash bin to measure the unfilled level. A RFID reader was interfaced with an ESP8266 module to upload the data to a server through an access point. In [21], an ultrasonic sensor was interfaced directly with an ESP8266 module to measure the unfilled level of trash bins.

From inferences obtained from the state-of-the-art research on smart trash bins, it is evident that the IoT based trash bin level monitoring systems are superior to the other conventional systems in terms of robustness and cost-effectiveness. Nevertheless, it is lagging to achieve efficiency in terms of power consumption and wide range network coverage.

A comparative study of existing wireless sensor networks, and IoT enabled trash bin level measurement systems is presented in table I. From the table, it is observed that the wireless communication technologies such as Zigbee, SimpliciTI, and Wi-Fi are short range. It require repeaters to establish long-range communication and it ultimately result in increased power consumption and complex system design.

A comprehensive study on smart city development based on long-range communication technology is presented in [22]. This study emphasizes the IoT systems established with LoRaWAN networking protocol. LoRaWAN is well suited for applications that require long-range connectivity, low power consumption, and distributed wireless sensor nodes [23]. These features of LoRaWAN networking protocol can overcome the limitations of existing IoT based trash bin level monitoring systems.

A smart waste collection system with LoRaWAN nodes is presented in [24]. This system uses multiple sensors such as temperature sensors to measure temperature inside a garbage bin, load cells to measure the weight of the garbage bin and an ultrasound sensor to measure the unfilled level. However, the use of multiple sensors consumes more power that leads to changing the battery often. Also, no practical results were provided on sensor node transmission range. Recently, a LoRaWAN network based waste management system in an university is presented in [25]. This system uses the Dijkstra's algorithm to evaluate the shortest path for waste collection. A maximum transmission distance of 1619 m is reported in this paper. However, no experimental results were provided on energy harvesting and visualization of data.

Hence, there is a need for a flexible IoT system that enables solar energy harvesting, long range data transmission, Geolocation of trash bins, ease to scale, cost effective, provides reliable information in real time to municipality or the solid waste management company. Therefore, to meet the needs of the municipality or the solid waste management company, we have developed an IoT system. The main features of our system are as follows:

- long-range data transmission
- solar energy harvesting with maximum power point tracking
- GPS unit to collect trash bin location
- battery protection and status indicator
- long-time data storage
- a smart graphical user interface to view the status of trash bins and its location in real-time

The rest of this paper is organized as follows: Section II describes the designing of the proposed IoT-TBLMS which includes the network architecture, design of the TBLMU, LoRaWAN gateway, and IoT-TBLM server. Section III shows the experimental results which includes testing of the IoT-TBLMS, wireless range between a TBLMU and a LoRaWAN gateway, the average current consumption of the TBLMU, life expectancy of the TBLMU, battery charging time, performance of the solar panel in a weatherproof enclosure, and cost. Section IV concludes the paper.

II. IoT-Trash Bin Level Monitoring System

A. Network Architecture of the Proposed IoT-TBLMS

The IoT-TBLMS employs LoRaWAN architecture in which the IoT-system is deployed in a star-of-stars network topology as shown in Fig. 1. Therefore, the wireless communication between a TBLMU and a LoRaWAN gateway is a single-hop link, takes advantage of long-range characteristics of the LoRa physical layer.

A TBLMU measures the unfilled level of a trash bin and its location, and transmits to a LoRaWAN gateway at a frequency of 915 MHz. Following, the LoRaWAN gateway receives the data from all the TBLMUs and forwards to a LoRaWAN gateway bridge. The software running on the LoRaWAN gateway forwards the packets called LoRaWAN gateway packet forwarder. Then, the LoRa gateway bridge receives the UDP packets and converts into JSON data format. Further, the mosquitto message broker present in between the LoRa gateway bridge and the LoRa network server implements Message Queuing Telemetry Transport (MQTT) protocol to carry data to the IoT-TBLM server for storage and analysis using a publish/subscribe model. Subsequently, users can view and analyze the level of all trash bins and their locations using a smart graphical user interface.

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TABLE I
COMPARISON OF EXISTING TRASH BIN LEVEL MONITORING SYSTEMS.

Ref. & Year	Radio technology	Network type	Power consumption	Wireless range	Energy harvesting	Geo-location of trash bins	Storage	Visualization
[09], 2012	Zigbee	WLAN	Low	Short	No	No	Yes	Yes
[10], 2014	No radio	-	-	-	No	No	No	No
[11], 2017	SimpliciTI	WLAN	Low	Short	No	No	Yes	Yes
[12], 2017	SimpliciTI	WLAN	Low	Short	Yes	No	Yes	Yes
[20], 2019	Wi-Fi	WLAN	High	Short	No	No	Yes	No
[21], 2019	Wi-Fi	WLAN	High	Short	No	No	No	Yes
[25], 2018	LoRaWAN	WWAN	Low	Long	No	No	Yes	No
[26], 2020	LoRaWAN	WWAN	Low	Long	No	No	Yes	No
Proposed system	LoRaWAN	WWAN	Low	Long	Yes	Yes	Yes	Yes

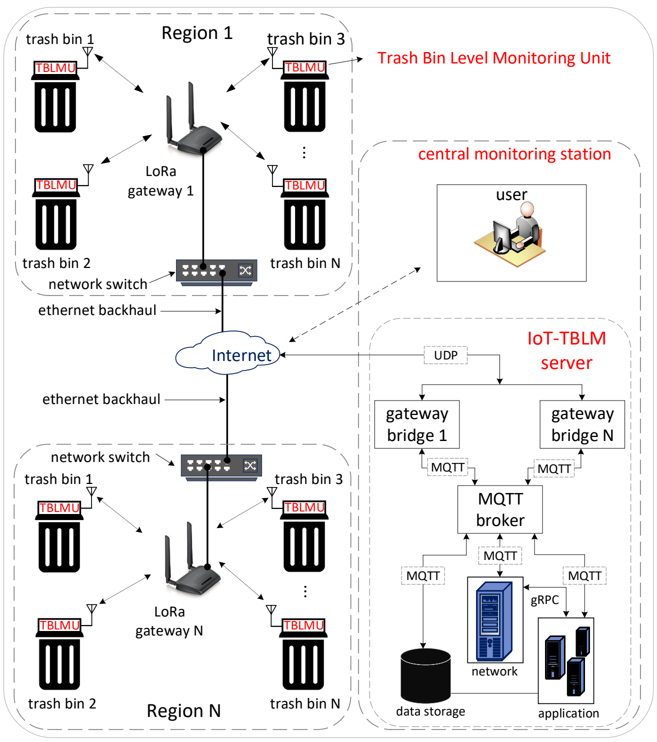

Fig. 1. Network architecture of the proposed IoT-TBLMS.

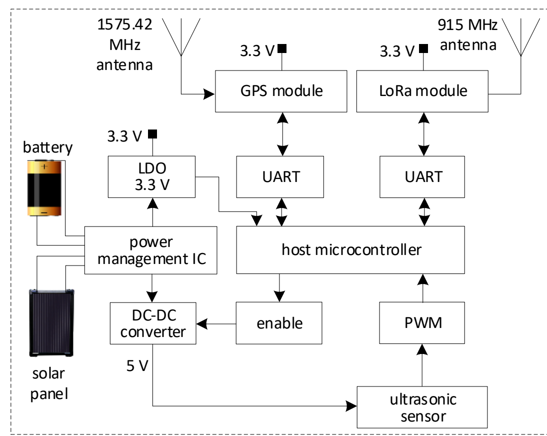

Fig. 2. Block diagram of the TBLMU

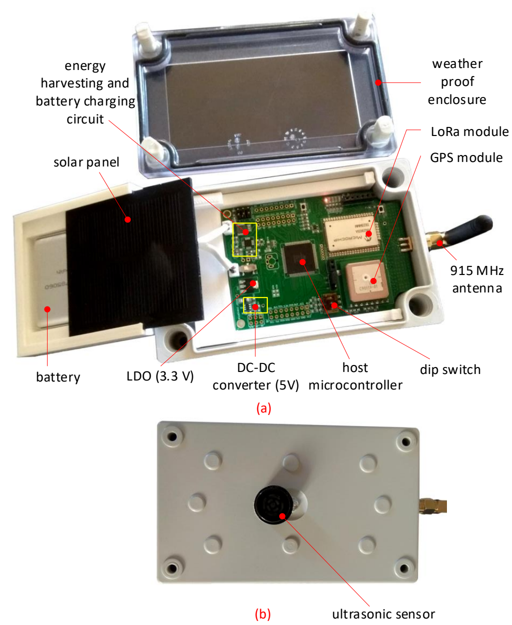

Fig. 3. (a) various parts of the TBLMU. (b) backside of the weatherproof case shows the installation of an ultrasonic sensor.

B. Trash Bin Level Measurement Unit (TBLMU)

A TBLMU mainly comprises of an ultrasonic sensor to measure the unfilled level of a trash bin, a GPS module to collect geographical location, a host micro-controller to process the data, a LoRa module for wireless transmission, and a power management unit. The block diagram of the TBLMU is portrayed in Fig. 2, and the prototyping and installation of the TBLMU in a trash bin are shown in Fig. 3 and Fig. 4, respectively.

1) Ultrasonic Sensor: The TBLMU uses an ultrasonic sensor to measure the unfilled level of bins. The choice of the appropriate ultrasonic sensor is a key factor in the design of the TBLMU. In order to provide efficient and reliable operation, we have preferred MB1010 LV-Maxsonar-EZ1. It is a low cost, high performance and stable range detector with quality beam features. The operating voltage of the sensor lies between 2.5 V and 5.5 V with a typical current consumption of 2 mA. This sensor can sense the obstacles up to a maximum range of 645 centimeters and ideally does not have any dead zone in the vicinity of the sensor range. Analog voltage, RS232 serial,

Fig. 4. Installation of a TBLMU.

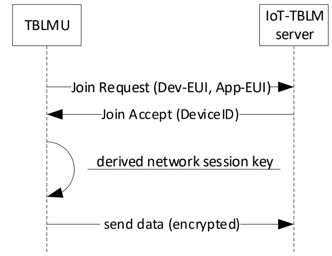

Fig. 5. Joining process of a TBLMU with the IoT-TBLM server

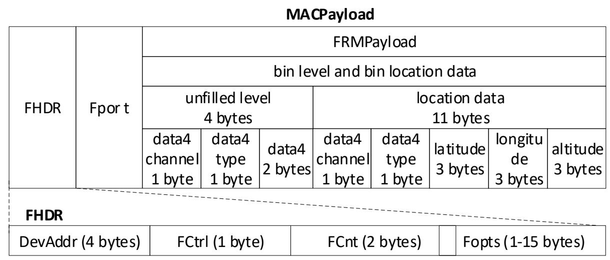

Fig. 6. MACPayload with Cayenne Low Power Payload of a LoRa uplink message

and pulse-width are the simultaneous output formats available for the sensor to interface with the host micro-controller. In the TBLMU design, the sensor was interfaced with the host micro-controller via a pulse width output format.

2) GPS Module: When managing solid waste in a wide area, numerous trash bins need to be installed. Location data of every trash bin is mandatory for the truck to collect garbage. Recording manually the geolocation data of numerous trash bins is a tedious process. In addition, the geolocation data helps to identify the relocated trash bins, stolen trash bins, and the central monitoring station to evaluate the shortest and best path for efficient garbage collection. In order to collect the geolocation coordinates of every bin, the TBLMU is equipped with a GPS module (PAM-7Q). The features of the PAM-7Q are, embedded antenna, high sensitivity of -161 dBm and sophisticated interference suppression which ensures maximum performance even in hostile environments. In order to reduce the average current consumption of the TBLMU, the GPS module was configured in the power save mode called ON/OFF operation. The power save mode operations are controlled through serial commands by the host micro-controller.

3) LoRa Module: The IoT-TBLMS uses the LoRaWAN networking protocol in which the communication between a TBLMU and the gateway is spread out on different frequency channels which uses the US902-928 MHz ISM band in pseudo-random fashion for every transmission to make the system more robust to interference. In order to transmit data to a long distance with low power, we use a RN2903 transceiver module. The RN2903 module is powered with a DC voltage of 3.3 V and interfaced with the host micro-controller via an UART.

4) Wireless Communications: A wireless connection must be established between a TBLMU and the central IoT-TBLM server to send and receive data. Hence, RN2903 uses a joining procedure called Over-The-Air Activation (OTAA) to join to the IoT-TBLM server which is described in Fig. 5. Once the connection is established successfully, the TBLMU starts sending the encrypted LoRa uplink message with Cayenne Low Power Payload (LPP). The MACPayload with Cayenne Low Power Payload of a LoRa uplink message is shown in Fig. 6. Whenever, TBLMU loses the network session context information, it must go through a new join procedure.

5) Host Micro-controller: The core of the TBLMU is the host micro-controller. It is responsible for controlling the TBLMU. The preferred host micro-controller is an 8-bit Atmel ATmega 2560 micro-controller. The main features are high performance, ultra low power (low power core which consumes 500 μA in active mode and 0.1 μA in power-down mode), and advanced RISC architecture[1].

6) Power Management Unit: The comprehensive circuit of the power management unit is shown in Fig. 7. The power management unit consists of an energy harvesting and battery charge circuit, a DC to DC converter, and a low-dropout regulator. The energy harvesting integrated chip BQ25505 features input voltage regulation which prevents the collapse of a solar cell, battery status indicator, and integrated maximum power point tracking. In order to prevent the Li-Ion battery from being deeply discharged and damaged, and to prevent excessive loading BQ25505 was programmed as 3 V as under-voltage threshold and 4.2 V as an over-voltage threshold. The DC-DC converter MCP16252T is used to boost to 5 V to power up the ultrasonic sensor. Likewise, a low-dropout regulator MCP1825S is used to regulate the voltage level at 3.3 V to power up the host micro-controller, LoRa module and the GPS module.

[1]Microchip, ATmega640/V-1280/V-1281/V-2560/V-2561/V, 2020.

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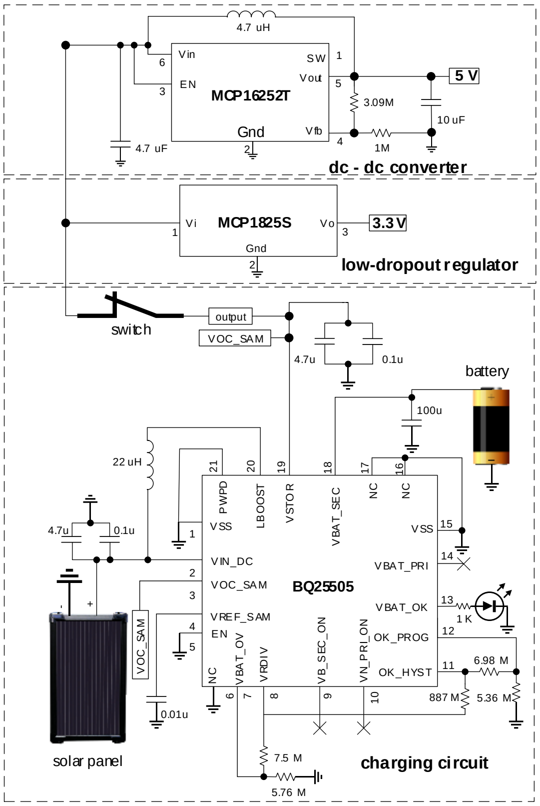

Fig. 7. Power management unit of the TBLMU.

C. LoRa Gateway

In favor of providing a robust connection between the IoT-TBLM server and a massive amount of TBLMUs, we have employed a commercially available microchip LoRa gateway which adopts Semtech SX1301 chip. Semtech SX1301 digital baseband chip is a massive digital signal processing engine specifically designed to offer breakthrough gateway capabilities in outdoor environment. Further, the gateway IP address, network ID, default subnet mask, server IP, server port for uplink messages, and server down port were configured according to the IoT-TBLMS.

The gateway consists of a core board and a LoRa radio board. The microcontroller present in the core board captures the data sent by the radio board and wraps it into JSON structure before forwarding to the Ethernet controller. Then, the Ethernet controller encapsulates the packets with UDP header, and forwards the packet to the IoT-TBLM server.

D. IoT-TBLM Server and Smart Graphical User Interface

The IoT-TBLM server programs were installed in a personal computer with Ubuntu 20.04 LTS operating system. The software architecture of the IoT-TBLM server is shown in Fig. 8. The software package comprises of open source programs such as Eclipse Mosquitto, ChirpStack server stack and a smart graphical user interface. The ChirpStack server consists of ChirpStack gateway bridge, ChirpStack network server and ChirpStack application server.

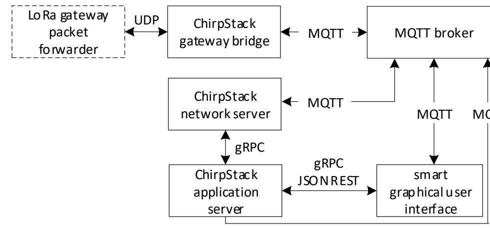

Fig. 8. Software architecture of the IoT-TBLM server

The ChirpStack network server implements the LoRaWAN network. Furthermore, it is responsible to eliminate duplicate packets, manages security and data rates. The ChirpStack application server is responsible to handle the join process of the TBLMUs and decoding of the application payload. Once the data from a TBLMU is decoded, then it is systematically stored in the postgreSQL database. The smart graphical user interface was developed by using C Sharp programming language based on .NET architecture. The graphical representation of the main window, region icons and the bin icons are graphically mapped according to the TBLMU measurement. In order to identify the trash bin level in a quick glance, different color codes are used for different levels. The height (maximum unfilled) of the trash bin used in the proposed IoT-TBLMS is 76.6 cm. Considering TBLMU measurements and maximum unfilled level of trash bins, smart graphical user interface maps each trash bin to a color code. The threshold levels used in the developed IoT-TBLMS are presented in table II.

TABLE II
THRESHOLD LEVEL OF THE SMART GRAPHICAL USER INTERFACE

unfilled bin level (cm)	**color of the filled area**	**status**
unfilled level = 76.6	green	empty
unfilled level >70	green	lightly filled
30<unfilled level <70	orange	partially filled
unfilled level <30	red	almost full

The screenshot of the developed smart graphical user interface is shown in Fig. 9, which displays the overall status (main icon), regional icons (different regions), and trash bins present in Region 1. The smart graphical user interface was developed in a hierarchical view to monitor the exact trash bin level and its location in real time. The main icon (overall status) of the smart graphical user interface is a progressive bar, which is synchronized to all TBLMUs present in the IoT-TBLMS. The color code of the main icon is mapped to the lowest unfilled value of the trash bins in the IoT-TBLMS. When the user clicks on the main icon, the smart graphical user interface opens another window which displays the regional icons. The region icon also serves as a progressive bar in which the status depends on the unfilled value of TBLMUs present in that region. The color code of the region icons is mapped to the lowest unfilled level value of the trash bins present in that region.

When the user clicks the region icon, the smart graphical user interface displays all the trash bins present in that region.

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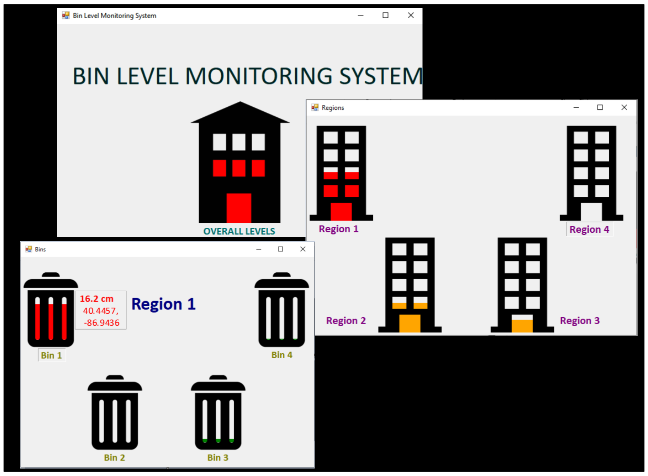

Fig. 9. Screenshot of the smart graphical user interface: main window displays the overall status of the system with a color code; region icons show different regions with color codes; trash bins present in the Region 1, displays the unfilled levels with color codes, and Bin 1 displays the unfilled level and its geolocation coordinates in red color.

However, the trash bin icons also serve as a progressive bar in which the status depends on the sensor value (TBLMU). From the Fig. 9, it is observed that the main icon color is red since the unfilled value of trash bin 1 is 16.2 cm which is less than 30 cm (threshold value) draws immediate attention to the user stating that, at least one trash bin in the IoT-TBLMS is almost full. Likewise, the region icons show different colors, Region 1 is red in color since the unfilled value of trash bin 1 is 16.2 cm. Similarly, Region 2 and Region 3 are in orange color since the unfilled level of the trash bins lies between 30 cm and 70 cm. Likewise, Region 4 is green in color since the unfilled level of all bins present in Region 4 are greater than 70 cm. When the user keeps the cursor or clicks over the trash bin, it displays the exact bin value and its geolocation coordinates.

III. Experimental Evaluation

A. *Testing of the Developed IoT-TBLMS*

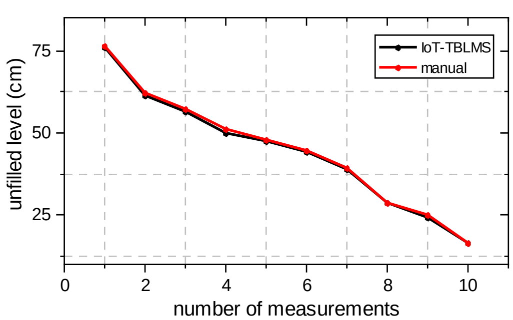

Fig. 10. Comparison of the IoT-TBLMS's measurements and manual measurements, were the waste present as smooth flat surface.

In order to analyze the accuracy of the developed IoT-TBLMS, a comparison study was carried out between the IoT-TBLMS's measurements and manual measurements. Therefore, a trash bin (Bin 1) was lightly filled with waste (clothes), the corresponding IoT-TBLMS's data and the manual data were noted. The IoT-TBLMS's data was stored in the IoT-TBLM sever, whereas the manual data was measured using a line gauge. Similarly, the unfilled level was measured for different levels of waste (clothes, bottles, shoes and card boxes) and shown in Fig. 10. From the figure, it is observed that the IoT-TBLMS's data and the manual data are close to each other. Notably, there is a difference between 0 - 0.9 cm, due to the surface level of waste present in the trash bin. However, the accuracy of the system depends on the sensor mounting position, beam width of the sensor employed (sensor should be selected according to the size of the trash bin), and the shape of the trash bin. Furthermore, trash bins that are equipped with plastic bags may detect false reflections if there is air trapped behind the plastic bag.

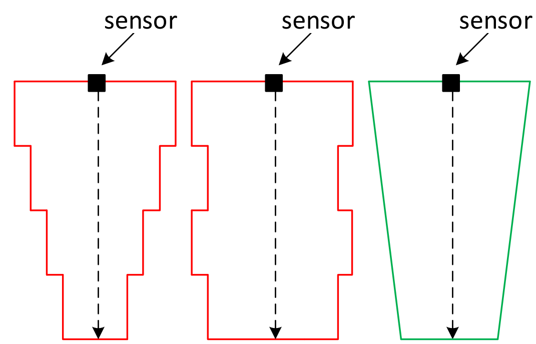

Fig. 11. Sensor mounting position, and shape of the trash bin. Red color bins: not recommended, Green color: recommended.

1) Recommended Sensor Mounting Position and Shape of the Trash Bin: Sensor mounting position and shape of the trash bin plays a vital factor to reduce the reflection errors. Therefore, the recommended sensor mounting position, and the shape of the trash bins are shown in Fig. 11. In red color bins, the sensor will range to the first indentation in the trash bin. This indentation creates a large detectable reflection, whereas the green color bin typically operates properly. In order to either eliminate or drastically reduces the secondary reflections that may return to the sensor due to the surface level of waste present in the trash bin, it is recommended that the sensor must be mounted in a trash bin as shown in Fig. 11 (Green color).

2) Mounting Multiple Sensors for Large Bins: The size of the trash bin employed in our experiment was 46 cm x 46 cm (top) and 33 cm x 33 cm (bottom). As the trash bin size increases, the less likely the sensor detects unwanted objects and noise. However, larger trash bins require multiple sensors. When interfacing multiple sensors in a single TBLMU, there must be interference (cross-talk) between sensors. Therefore, the employed sensor introduces a concept called chaining, and the connection of multiple sensors into a single TBLMU is shown in Fig. 12.

To command a range cycle of N sensors, enable the Rx pin of the host micro-controller high for a time period in between 20 μS and 48 mS, and return to ground. This will initiate the sensor chaining process. Immediately, sensor 1 measures the unfilled level, then triggers the sensor 2 to measure, and

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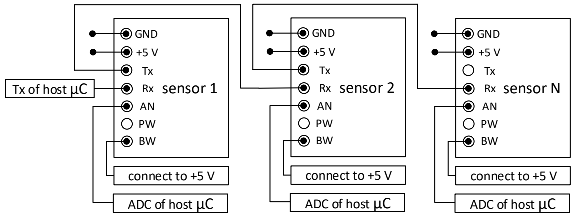

Fig. 12. Circuit diagram for connecting multiple sensors for larger bins

so on. Once the Nth sensor has measured the unfilled level, the chaining process stops. This process is repeated for every 5 minutes. Likewise, as the trash bin size (width) decreases, narrow beam sensors are required.

B. Wireless Range between a TBLMU and a LoRaWAN Gateway, and Packet Loss Rate

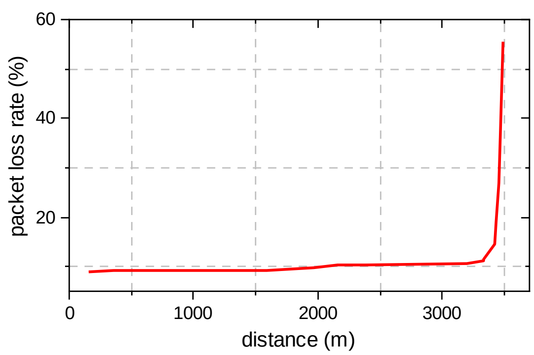

Fig. 13. Measured maximum wireless transmission distance between a TBLMU and a gateway with respect to Packet Loss Rate at a power level of 10 dBm, spreading factor of 7, coding rate of 4/5, bandwidth of 125 KHz, and gateway antenna height of 26 feet from ground surface.

To evaluate the wireless range, the maximum wireless transmission distance between a TBLMU and a LoRaWAN gateway was measured. This experiment was carried out in an open space (partially line of sight), where the antenna of the LoRaWAN gateway was installed vertically at a height of 26 feet from the ground surface, and kept immovable. The firmware of the TBLMU was programmed to transmit 4000 frames at each distance. Then, the TBLMU was moved to various distances from 20 m to 3486 m and the corresponding Packet Loss Rate (PLR) was evaluated as follows:

$$PLR = T_{PL}/T_{PT} \tag{1}$$

where, T_{PL} is the total number of packets lost and T_{PT} is the total number of frames transmitted by the TBLMU successfully. From the Fig. 13, a PLR of 10.75% and below is achieved for a distance up to 3200 m at the transmission power of 10 dBm. The PLR of 10.75% and below is acceptable for trash bin level monitoring since the TBLMU can transmit data for every 5 minutes. From this experiment, it is observed that the trash bin level can be monitored without any practical degradation in the signal at a radius of 3200 m from a LoRaWAN gateway. Additional coverage area can be achieved by increasing the spreading factor up to 12, increasing the height of the antenna and by installation of additional gateways. However, increasing spreading factor increases Time on Air (ToA) between a TBLMU and a LoRaWAN gateway. When

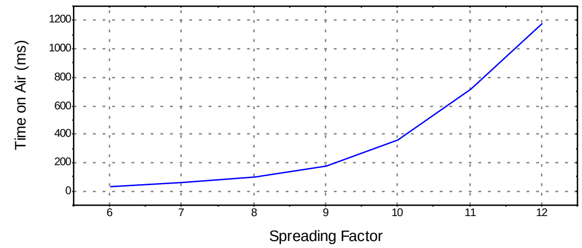

Fig. 14. Calculated time on air between a TBLMU and a LoRaWAN gateway with respect to spreading factors.This calculation was carried out with a payload of 15 Bytes, coding rate of 4/5, bandwidth of 125 KHz, and programmed preamble of 8 symbols.

a signal is sent from a TBLMU, it takes a certain amount of time before a LoRaWAN gateway receives, this signal is called ToA. This ToA was calculated by using a LoRa calculator from the Semtec and shown in Fig. 14. From the figure, an important consequence is observed that the higher spreading factor for LoRa takes longer time on air. This means that the power consumption of the LoRa radio module increases with increasing spreading factor. Hence, to optimize the spreading factor, adaptive data rate can be employed. Depending on the environmental conditions between the TBLMU and the LoRaWAN gateway the network will determine the best spreading factor to send the data.

C. Average Current Measurement of the TBLMU

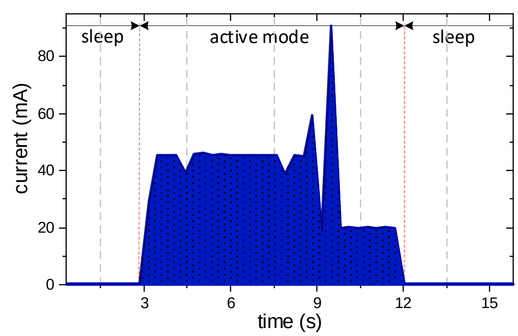

Fig. 15. Measured current consumption of the TBLMU in active and sleep mode. The LoRa module was operated at a power level of 10 dBm, spreading factor of 7, coding rate of 4/5, and bandwidth of 125 KHz.

To estimate the life time of the TBLMU, we have measured the current consumption of the TBLMU using a 16-bit ultra precise INA233 current monitor. The measured current consumption of the TBLMU in active and sleep mode is illustrated in Fig. 15.
Current contribution of the TBLMU in active mode

$$\begin{aligned} Q^a_{TBLMU} = & ([I^q_{EH} + I^q_{LDO} + I^q_{DC-DC} + I^a_{HM}] \\ & \times T^a_{HM}) + (I^a_{GPS} \times T^a_{GPS}) + \\ & (I^a_{LM} \times T^a_{LM}) + (I^a_{sensor} \times T^a_{sensor}) \\ = & \; 0.3316 \; A \times s \end{aligned} \tag{2}$$

where, I^q_{EH} - quiescent current of the energy harvesting integrated chip (BQ25505), I^q_{LDO} - quiescent current of the

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LDO (MCP1825S), I^q_{DC-DC} - quiescent current of the DC-DC converter (MCP16252T), I^a_{HM} - current consumption of the host micro-controller in active mode (ATmega2560), T^a_{HM} - time period of the host micro-controller in active mode, I^a_{GPS} - active current consumption of the GPS module (PAM-7Q), T^a_{GPS} - time period of the GPS module in active mode, I^a_{LM} - current consumption of the LoRa module in active mode (RN2903), T^a_{LM} - time period of the LoRa module in active mode, I^a_{sensor} - current consumption of the ultrasonic sensor in active mode, T^s_{sensor} - time period of the ultrasonic sensor in sleep mode.

The less frequently that a TBLMU measures the trash bin level, the more significant that the sleep current's contribution to the overall average current transmute.
Current contribution of the TBLMU in sleep mode

$$Q^s_{TBLMU} = (I^q_{EH} + I^q_{LDO} + I^q_{DC-DC} + I^s_{HM} + I^s_{LM}) \times (T - T^a_{HM}) \tag{3}$$

$$= 0.382 \times 10^{-3}\ A \times (300\ s - 8.216\ s) = 0.1115\ A \times s$$

where, I^s_{HM} - current consumption of the host micro-controller in sleep mode, I^s_{LM} - current consumption of the LoRa module in sleep mode, T - period of trash bin level measurement (300 s), T^a_{HM} - active time period of the host micro-controller.
Average current consumption of the TBLMU

$$I_{TBLMU} = \frac{Q^a_{TBLMU} + Q^s_{TBLMU}}{T} = 1.5\ mA \tag{4}$$

D. Life Expectancy of the TBLMU

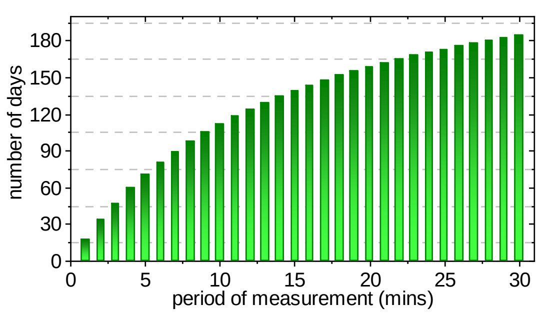

Fig. 16. Life expectancy of the TBLMU

The life expectancy of the TBLMU was evaluated under the hypothetical condition, in which the voltage of the energy source is ideal until its capacity is drained out. The life expectancy of the TBLMU is estimated as follows

$$O_d = Q_B / I_{TBLMU} \tag{5}$$

$$\approx 69\ days\ 10\ hours\ 40\ minutes$$

where, O_d is the total days of operation of the TBLMU, Q_B is the capacity of the battery used. Fig. 16 shows the estimated life time of the TBLMU for different time period of trash bin level measurement. Notably, the trash bin level can be measured even for every minute which allows the municipality or the solid waste company to manage municipal solid waste efficiently.

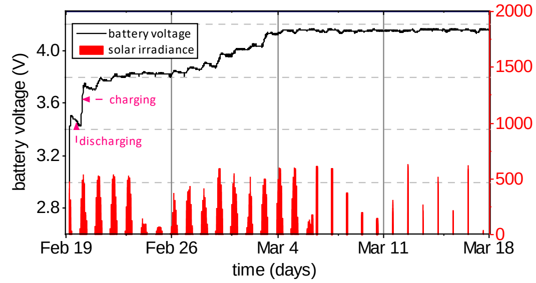

Fig. 17. Measured battery voltage with the load (transmission power of 18.5 dBm) and the corresponding solar radiation (Lat: +40.471, Lon: -86.992), period of measurement is 10 minutes.

E. Estimation of Battery Charging Time

Another significant experiment has been carried out to estimate the battery charging time. The battery used in this experiment was a Li-ion battery with a capacity of 2500 $mA \times h$. The battery charging time defined in this experiment is the time taken to charge the battery from 3 V (under-voltage threshold) to 4.20 V (over-voltage threshold) with reference to the solar radiation. The Li-ion battery was discharged up to 3 V, and connected to the energy harvesting circuit for charging. When the solar radiation was 473 W/m^2, the load was switched ON. The energy which was harvested by the solar panel was shared by the load and the battery. Fig. 17 shows the battery voltage with reference to the solar radiation. From the figure, it is observed that the battery voltage increases during day time and the battery voltage decreases during night time due to the load. Notably, the total time to charge the battery was approximately 16 days with respect to the measured solar radiation.

In summary, once the battery is fully charged, the battery charge can last long for 69 days 10 hours. Therefore, the status of the trash bins can be monitored ideally without any interruption even during rainy days or cloudy days.

F. Performance of the Solar Panel in a Weatherproof Enclosure

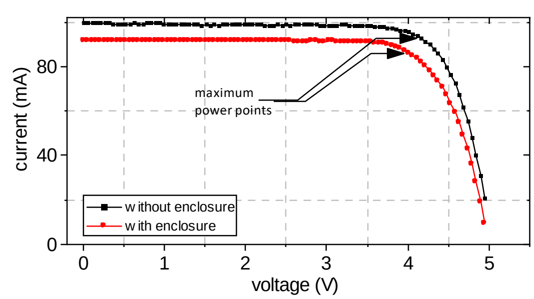

Fig. 18. Measured IV characteristics of the solar panel with a weather proof enclosure and without a weather proof enclosure.

In order to protect the TBLMU from the environment, the TBLMU is enclosed with a NEMA 4 rated weatherproof case. The weatherproof case is fabricated with polycarbonate material and the cover is fabricated with fiberglass. To protect the solar panel from the weather, the solar panel was installed inside the weatherproof case. An experiment was carried out to evaluate the maximum power that can be harvested by the

TABLE III
PARTS COST OF A TRASH BIN WITH A TBLMU

Items	Cost in USD
LoRa Module (RN2903)	12.05
host microcontroller (ATmega 2560)	10.24
GPS module (PAM-7Q)	22.4
energy harvesting integrated chip (BQ25505)	3.97
DC-DC converter (MCP16252T)	0.45
trash bin	17
LDO (MCP1825ST)	0.4
915 MHz antenna	10.55
battery 3.7 V, 2500 mAh	14.95
solar panel	11.34
miscellaneous (resistors, capacitors, inductors, connectors and so on)	11.63
printed circuit board	10.77
weather proof enclosure	10.1
ultrasonic sensor	26
Total cost	**161.85**

solar panel and the percentage of solar energy resisted by the weatherproof transparent enclosure.

The measured IV-characteristics of the solar panel is shown in Fig. 18. From the figure, the maximum power generated with the enclosure is 10.45% lesser than the power generated without an enclosure. However, even with 10.45% of reduction, the solar panel generates 345.75 mW (977 W/m^2) of power which is sufficient to recharge the battery.

G. Cost

The cost of a IoT-TBLMS includes the cost of a trash bin with a TBLMU, a LoRa gateway, a fiberglass antenna, and a personal computer. The purchase cost of a trash bin with a TBLMU is summarized in Table. III. Likewise, the purchase cost of a Microchip LoRa gateway is $360, fiberglass antenna is $43 and a personal computer (Dell Inspiron-3471-desktop) is $499.99. However, the developed IoT-TBLMS may be cost-effective if commercially fabricated by purchasing large quantity of items.

H. Comparison of Results

A summary of our experimental results is shown in table IV, and are compared with the existing LoRaWAN based trash bin level measurement systems reported in [24] and [25]. These systems were deployed and tested in a real time scenario. However, the important parameter of a LoRaWAN networking protocol is the wireless range, and the current consumption. In [24], the wireless range is not validated practically and the wireless range of the proposed system at a transmission power of 10 dBm is 50% higher than the system reported in [25]. Furthermore, the current consumption of the proposed system is much lower than [24] and [25]. For instance: the current consumption in active mode of the ultrasonic sensor employed in [24] and [25] is 15 mA, whereas the ultrasonic sensor employed in the proposed system consumes 2 mA. Additionally, the parameters such as life expectancy, battery charging time, performance of the solar panel, and the cost were studied and reported in the proposed system, whereas these variables are not reported in [24] and [25].

TABLE IV
SUMMARY OF RESULTS

experiment	result
1. testing	a trash bin was filled with waste and the corresponding unfilled level was monitored in the smart graphical user interface.
2. wireless range	a wireless communication range of 3200 m was evaluated at a transmission power of 10 dBm with a 10.75% of packet loss rate.
3. current consumption and life expectancy	the average current consumption of the TBLMU is 1.5 mA. At this rate, the on-board Li-ion battery is able to sustain a TBLMU for 69 days 10 hours.
4. battery charging time	a 7 cm x 6.5 cm solar panel was able to fully charge the on-board battery in 16 days while supplying power to the TBLMU.
5. performance of solar panel	the solar panel generates 345.75 mW of power inside an IP67 transparent enclosure.
6. cost	total cost of a trash bin is 161 USD.

Nevertheless, an algorithm for route optimization is reported in [24] and [25]. These results and the features listed in table I, demonstrate that the developed LoRaWAN based system is better than the existing LoRaWAN based systems to provide reliable trash bin level information in real time.

IV. CONCLUSION

This paper presented the development and validation of an IoT system to monitor the trash level and geolocation of trash bins efficiently. All aspects of an IoT system includes the design of a TBLMU, long range data transmission, long-time data storage, and visualization of trash bin level have been developed. Finally, the developed system was validated by evaluating the accuracy of the sensor employed, maximum transmission distance between a TBLMU and a gateway, life expectancy of a TBLMU, battery charging time and cost. Based on the results obtained, the proposed IoT system is suitable for Municipality or Municipal Solid Waste Management Companies to manage municipal solid waste efficiently.

Future work in this discipline, developing a deep learning algorithm to analyze the geolocation coordinates of almost filled and partially filled bins to create an optimized truck route.

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