



Design and Implementation of Collaborative Energy Efficient IoT-based LoRa WAN

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Abstract: - Wireless sensor network (WSN) architectures involve multiple sensor nodes that cover large areas. It is difficult to deploy such nodes efficiently. However, based on clustering and collaboration, WSNs can organize efficiently and prolong system lifetime. In this paper, we discuss the design and implementation of a collaborative LoRa WAN using ultra-low-energy hardware and smart utilization of battery power. We have chosen the robust LoRa modulation technique and clustering method to design the end nodes. The sensor data from each of the end nodes are transmitted using low-power, long distance, and noise-resilient LoRa radio channels to their corresponding Cluster Heads (CHs), where it is first stored and then processed before transmitting further to the Gateways. The storing and then transmitting technique reduces the bandwidth requirement significantly. Also, the stored sensor data can be analyzed for system optimization. Immediately after transmission, the microcontroller goes to hibernation mode, whereas, the sensor system and the LoRa module are powered off until the next cycle. In this way, the power consumption by the end node is kept at its minimum and the battery life is extended to 35 years. Several challenges related to hardware design and network parameters optimization to achieve energy-efficient IoT-based LoRa WAN are presented and discussed.

Keywords: Wireless Sensor Network, LoRa WAN, Modulation, Clustering

1. Introduction

A Wireless sensor network that is designed to sense and monitor the physical and environmental parameters consists of digital sensors, microcontrollers, and modems. We need an Internet-of-Things (IoT) based network to access the sensor data and control the actuators from anywhere in the world.



Most of the end nodes in the network are battery-operated and therefore it is necessary to design such networks with energy-efficient technology to increase the lifetime of the entire network. Network partitioning using a clustering algorithm is one of the energy-efficient solutions that has been proposed by the research community to gather data from a WSN [5]. Twentyseven different existing clustering algorithms over the last two decades have been discussed and compared in [18]. Most of the work is focused on solving energy efficiency issues for the extension of network lifetime. The study has been done on the selection and configuration of CHs. These approaches cannot be directly applied to LoRa networks. Also, other issues such as modulation techniques and hardware selection are often ignored. We have introduced a new technique, Collaborative Energy-Efficient IoT-based LoRa WAN, that is superior to other techniques for Internet of-Things (IoT) applications. Low- power protocols such as Zig-Bee, and Bluetooth, do not consider an acceptable combination of extended range and battery life. The new technology, LoRaWAN which operates in the sub-GHz range is capable of providing a long-range radio link over several kilometers with a very small amount of energy consumption [16], [17]. LoRaWAN along with a collaborative network provides efficient data sensing, storage, transmission, and query processing [3], [7]. The Collaborative LoRaWAN network architecture used in this work is depicted in Figure1. Since the LoRa technology allows semiduplex operation, all the nodes are capable of bi-directional communication as required in IoT-based systems.

Our network ensures coverage even in the absence of public networks. Each of the end nodes is powered on for a short duration decided by the corresponding CH. Furthermore, when powered on, they operate in deep sleep or hibernation mode, minimizing battery consumption. Here the LoRa channels are tuned to the license-free Industrial, Scientific, and Medical (ISM) bands permissible in the region of deployment, whereas Wi-Fi operates on a standard 2.4 GHz frequency band, both the bands are ITU standard. This network considers several factors such as long-range coverage, in-building penetration, less complexity in programming, and scalability to support future upgrades. LoRaWAN is subject to regulations at regional and national levels. Therefore, before designing and implementing LoRa WAN end nodes and gateways, one must pay attention to the specifications and configuration of these devices. In this work, we have designed a semi-private, semipublic network. The end nodes and the corresponding CHs are chosen to be private types and the rest of the network is public which strictly follows the LoRaWAN specifications. The end node which is configured as class-A type transmits without opening the usual receive windows which otherwise follow the transmit window after a specific time. This greatly simplifies the node design and reduces the active time of the microcontroller and LoRa module, resulting in less battery power consumption in a cycle.



2. Related Work and Contribution

A detailed introduction to LoRa and LoRa WAN technologies is provided in [2], [9], [10] [7, 8, 9]. In [9], by conducting field tests and simulations, the performance of the physical the range increased with the spreading factor (SF) and the maximum range (non-LOS) of 2800 meters could be achieved with SF12 in an urban environment. LoRa BER performance for different values of SF and two types of fading channels are studied in [9] and the authors noted that LoRa is not suitable for long-range communication in urban environments. In [12], the authors have focused on LoRaWAN characteristics such as range, delay, and throughput and successfully tested a 25 km LOS link with a coverage of 1380 sq km using SigFox and LoRa with three base stations at a height of 470 meters above mean sea level using 14dBm(25mW) transmitter power. Cattani analyzed [6] the performance and reliability of LoRa as a function of different physical settings and environmental conditions for three types of channels (underground, indoor, and outdoor), considering several LoRa parameter settings, such as SF, CR, BW, and BR. The authors have observed that high temperature at the node decreased the packet delivery rate considerably. The energy consumption model based on LoRa and LoRa WAN is discussed in [4], [14]. In [4], the impact of LoRa WAN parameters such as acknowledged transmission, coding rate, payload size, spreading factor, and communication range on the sensor node power consumption are studied. The authors have concluded that class A operation without acknowledgment window yielded maximum battery life which was about 5 years with a 950mAH capacity battery. A detailed explanation and illustration of LoRa WAN classes and their corresponding power consumption are discussed in [14]. The authors have conducted experiments for class A and in sleep mode, the current drawn was found to be 1.27mA which is about 700 times the theoretical value of 1.8 μ A. The battery life was further discussed based on the theoretical value and not the measured value and the battery life of 10 years is possible with a battery of 2200mAH capacity.

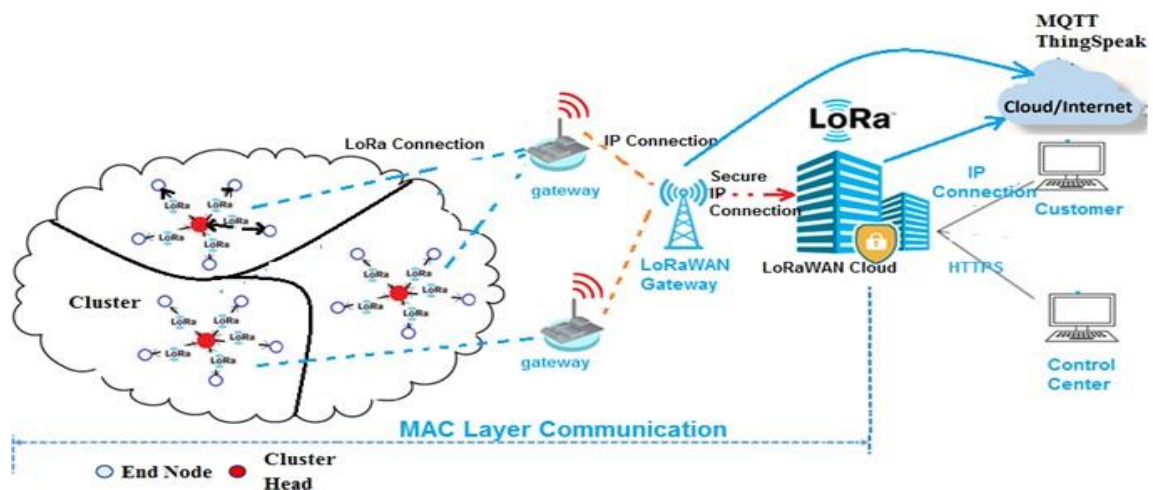


Fig. 1: Collaborative LoRa WAN Architecture.



In our work, we have used an all together different approach to reduce power consumption. First of all, the sensor data is transmitted and stored at the nearest CH without any acknowledgment. Secondly, the sensor system and LoRa modem remain in powered-off mode except for a short duration, whereas, the microcontroller operates in modem-sleep or hibernation mode, the total measured current drawn from the battery in this mode of operation is found to be less than 3 μ A. This technique resulted in a significant reduction of overall power consumption by the end node and the lifetime of the single 2200mAH is extended to 35 years.

3. Hardware Implementation

We have designed and implemented the end node and the cluster head (CH) using ultra-low power hardware. Each of the end nodes is a battery-operated embedded system. All the ICs used in the end node require a 3.3volt power supply that is derived from a Li-Po battery and a 3.3-volt LDO regulator. The end node consists of an ultra-low-power microcontroller, sensor system, LoRa modem, and actuators as shown in Figure 2. In the embedded system design the interfacing protocols at the physical layer play an essential role and it must allow the transparent connection to the network of additional devices [1]. A bus system is a communication path required for transmitting and receiving information between two or more devices.

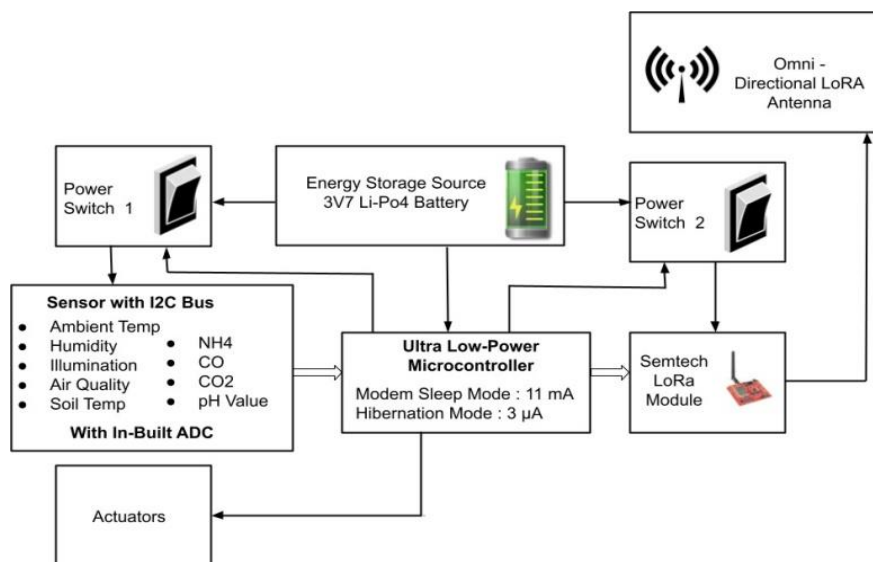


Fig. 2: Block diagram of Sensor Node.

USART, SPI, CAN, and Inter-Integrated-Circuit (I2C) are some of the different types of bus protocols available. An I2C bus protocol is an ideal choice for serial data transmission between microcontrollers and peripherals in a scalable WSN. A typical message packet with an I2C bus is shown in Figure 3a. We have connected several sensors to a single master and wired them as shown in Figure 3b.

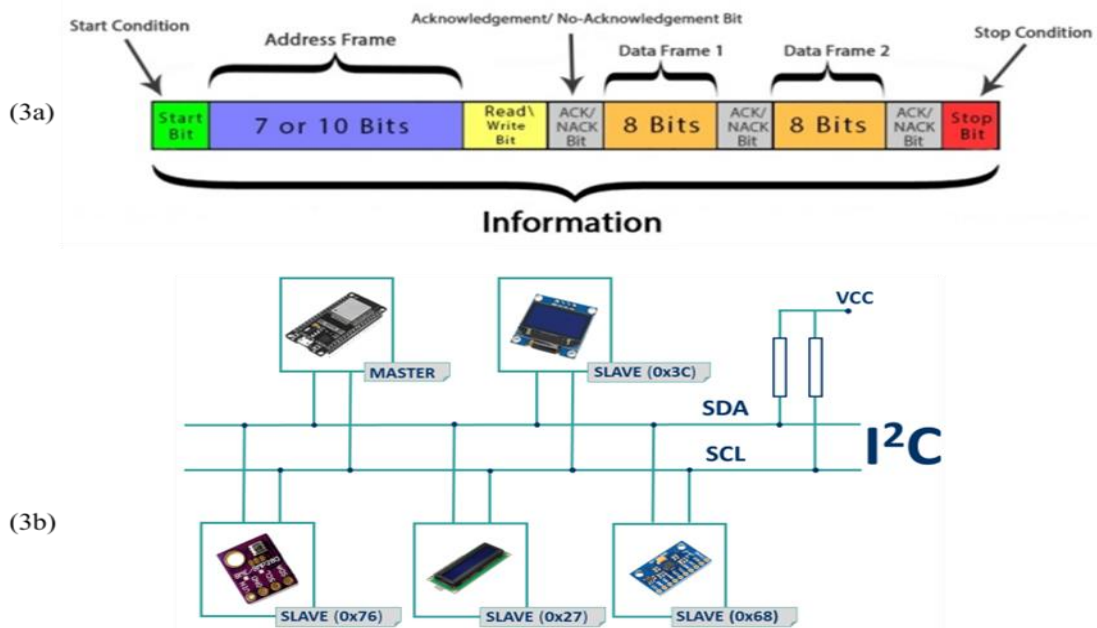


Fig. 3: (a). I2C Bus Message Frame; (b). Master-Slave Connection on I2C Bus

With a 7-bit address, 128 (27) unique addresses are available. All the slave devices don't respond unless their address is specified by the master device on the SDA line. With this connection, we can accommodate a maximum of 128 sensors at each end node. This capacity can be easily increased by a small variation in the hardware. Among the microcontrollers μ Cs available, we have used ESP32 by Espressif system, which is a System-on-Chip (SoC) solution and is an ideal choice for a wide variety of applications relating to the Internet of Things (IoT).

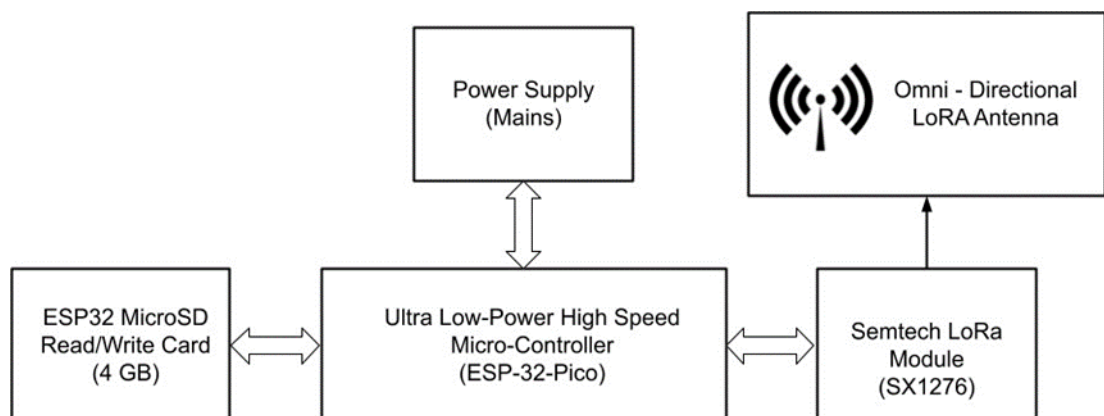


Fig. 4: Block diagram of Cluster Head.



Its main features and comparative study is provided in [11]. ESP32 family has several dedicated hardware security features required in an IoT application [13]. This microcontroller offers the following configurable power modes: hibernation mode, deep sleep mode, light sleep mode, modem sleep mode, and active mode. Different modes have different power-saving capabilities. During the active phase the μC at the end node operates in modem-sleep mode and the rest of the time it is operated in either deep-sleep or hibernation mode, wherein the power consumption is the least. Specifically, we have used the ESP32-WROOM-32D board for the end node design because it offers minimum currents both in deep-sleep and hibernation modes of operation. The LoRa modem is interfaced with the μC using an SPI port and its RF output is connected to an outdoor directional antenna to increase the range for a given transmitted power, also it helps in the re-usage of limited channel frequencies, thereby increasing the capacity of the network.

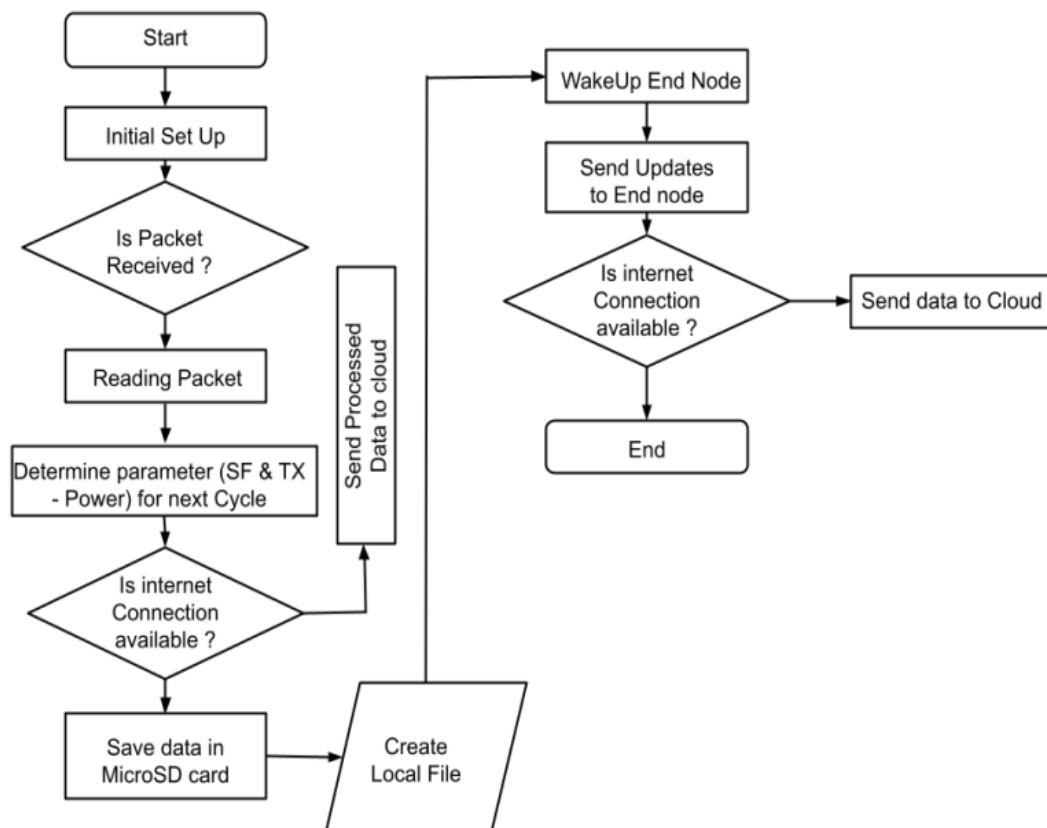


Fig. 5: Flow Chart of Cluster Head Sequence of operations.

LoRa WAN is a media access control (MAC) protocol, whereas, LoRa is a physical layer (PHY) implementation. The LoRa modem uses a chirp spread spectrum (CSS) modulation technique covering the entire channel bandwidth to broadcast a signal. This makes the system robust to channel noise and resistant to multipath, fading, and the Doppler effect, even at low



power. LoRa technology supports energy-efficient long-range communication permitting an increase in link budget at low power. In LoRa TM Modem, the spreading factor (SF), transmitter power (TP), and modulation bandwidth (BW) are design variables that allow the designer to optimize the system performance [8], [15]. LoRa uses license-free sub-gigahertz radio frequency bands. To comply with the IN865 band, we have implemented the system using the Semtech SX1276 LoRa chip. The CH is installed at a higher place to avoid Fresnel zone interference. The CH communicates with all the end nodes connected to it via LoRa channels and an Omni directional antenna to collect sensor data, GPS information, and battery-life information. The data thus collected will be first stored in an external MicroSD memory, processed using an ESP32-S2 microcontroller, filtered out necessary data for transmission, and then passed onto the gateway node. Whereas, the RSSI and battery-life information from the received packet is stored in the built-in flash memory. The algorithm determines the next cycle values of SF(SF7 to SF12) and TX power(7dBm to 17dBm). It then transmits these adaptive parameters to each of the end nodes within its cluster coverage. This procedure optimizes the data transfer for efficient bandwidth utilization and energy conservation, reducing the battery consumption significantly and thereby prolonging the lifetime of the entire network. The Cluster Head (CH) block diagram is shown in Figure 4 and the sequence of operations carried out by the CH is given in Figure 5.

4. Energy Consumption Model

Figure 6 depicts the working sequence, current consumption, and duration of different operating modes of the sensor node.

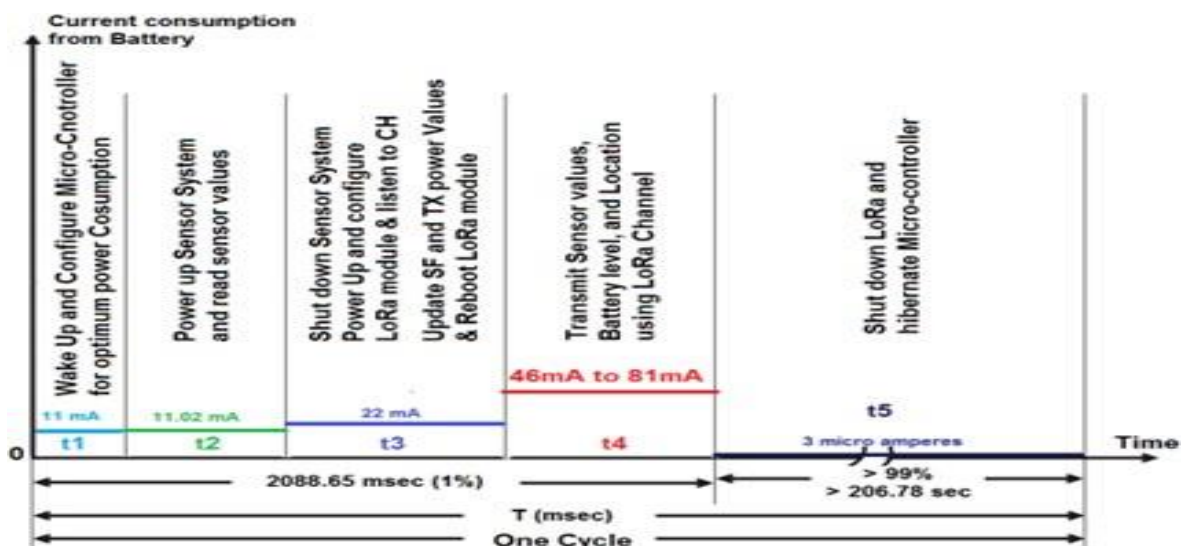


Fig. 6: End Node working scenario for one complete cycle.



TABLE I: The measured LoRa currents for different transmit-ter power

IX Power (dBm)	3	5	7	9	11	13	15	17
I _{LoRa} measured (mA)	28	32	35	40	45	50	55	70

TABLE II: The calculated various time slots as shown inFigure 6

Time	t ₁	t ₂	t ₃	t ₄	t ₅
msec	4.9	348.5	0.25	1735	T- (t ₁ + t ₂ + t ₃ + t ₄)

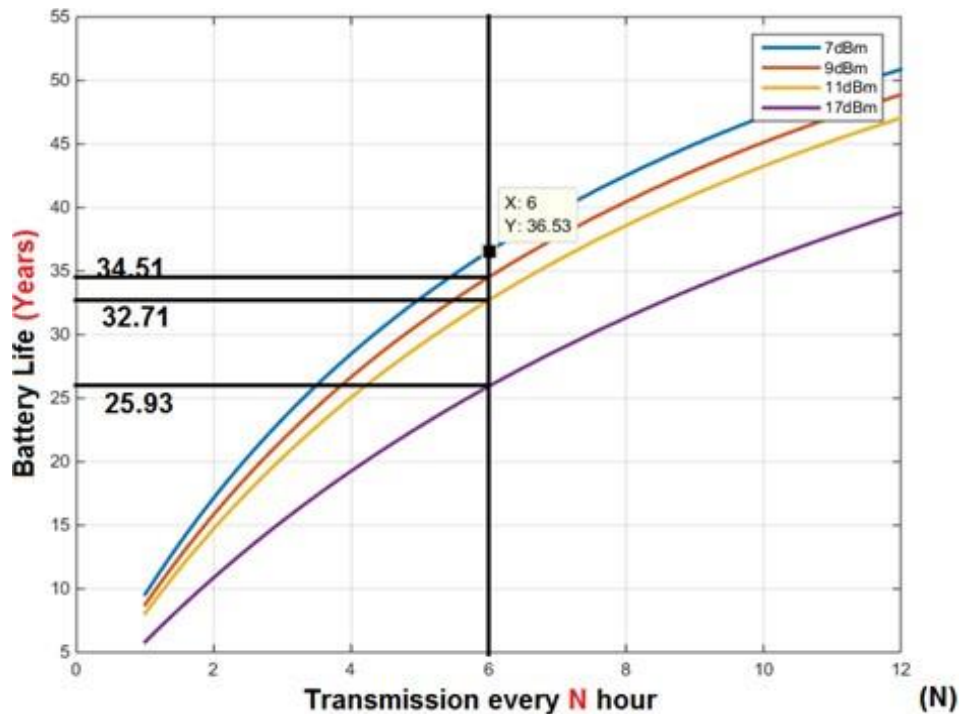


Fig. 7: Battery life in years for varying transmitter power.

The total energy consumed by each of the end nodes can be determined by knowing the current values and the corresponding duration for which each of the modes is active and is given by equation (1) below. Whereas, the measured values of LoRa currents and the various timings involved are given in Table 1 and Table 2 respectively.



$$E_{T\text{otal}} = 11*t_1 + 11.02*t_2 + 22*t_3 + (11 + I_{LORA}) * t_4 + 3*10^{-3}*t_5 \quad (1)$$

Substituting the values from Table 1 and Table 2 in equation (1), we get

$$E_{T\text{otal}} = 11*4.9 + 11.02*348.5 + 22*0.25 + (11 + I_{LORA}) * 1735 + 3 * 10^{-3} * T - 2088.65 * 103 \text{ mAS}$$

$$E_{T\text{otal}} = 11*4.9 + 11.02*348.5 + 22*0.25 + (11 + I_{LORA}) * 1735 + 3 * 10^{-3} * T - 2088.65 * 103 \text{ mAS}$$

$$E_{T\text{otal}} = [22978.61 + I_{LORA} * 1735 + 3 * 10^{-3} * T] * 103 \text{ mAS}$$

$$E_{T\text{otal}} = 22978.61 + I_{LORA} * 1735 + 3 * 10^{-3} * 3600 * 10^3 * N * 10^3 \text{ mAS}$$

$$E_{T\text{otal}} = [22978.61 + I_{LORA} * 1735 + 10.8 * N] * 103 \text{ mAS} \quad (2)$$

Here T is in msec, I_{LORA} is in mA and N is in hours. The battery life in years is given by,

$$B_{\text{Life}} = \frac{B}{[22978.61 + I_{LORA} * 1735 + 10.8 * N] \text{mAS} \frac{24}{N} 365}$$

$$B_{\text{Life}} = \frac{2200 * 3600 \text{ mAS}}{[22978.61 + I_{LORA} * 1735 + 10.8 * N] \text{mAS} \frac{24}{N} 365}$$

$$B_{\text{Life}} = \frac{904.11 * N}{[22978.61 + I_{LORA} * 1735 + 10.8 * N]} \quad (3)$$

Battery life as given in equation (3) is plotted for the N-hour cycle and depicted in Figure 7 below. It may be noted that the battery life depends on transmitter power and is more than 30 years for a transmitter power of 15 dBm or less.

4.1 Experimental setup

In this experiment, we have deployed two end nodes and a cluster head for testing purposes. The experimental setup is shown in Figure 8a, 8b, and 8c below. The end node and cluster head are tested by powering them ON continuously for six months, sending packets every single minute. Table 3 depicts the number of packets sent at the end of every month and the corresponding battery voltage. We note that at the end of six months the battery voltage has dropped down to 3.47 volts from its fully charged value of 4.07 volts and the nodes can continue to operate for some more time before the battery discharges to a critical



value of 3.2 volts. The equivalent number of years of battery usage is calculated, considering a 4-hour cycle, and every cycle we send 3 packets, that is we send 18 packets per day.

5. Results and Discussion

The transmitter parameters we have set in our design are spreading factor(adaptive), Signal Bandwidth(125kHz), Coding Rate4 (8), and TX power (adaptive). For testing purposes, the range from node1 to CH is kept at 100 meters, whereas, node 2 is about 500 meters away from the CH. We have 12 recovered all the LoRa packets from both node1 and node2 arriving at the same time or at different times and the records are shown in the table4 below along with corresponding RSSI values. Table4 Received sensor values along with RSSI From the above results and with a receiver having a sensitivity of -140 dBm, the maximum achievable range for LOS link wouldbe $D = 12$ km(approximate) which is a very good range for many LoRa WAN applications. The sensor readings received by the CH are posted on the Webpage as well as on the cloud after processing using IFTTT-Google Spread Sheet mobile appas given in Figure 9. Also, the location of the deployed nodeis indicated on the Google map as shown in Figure 10.

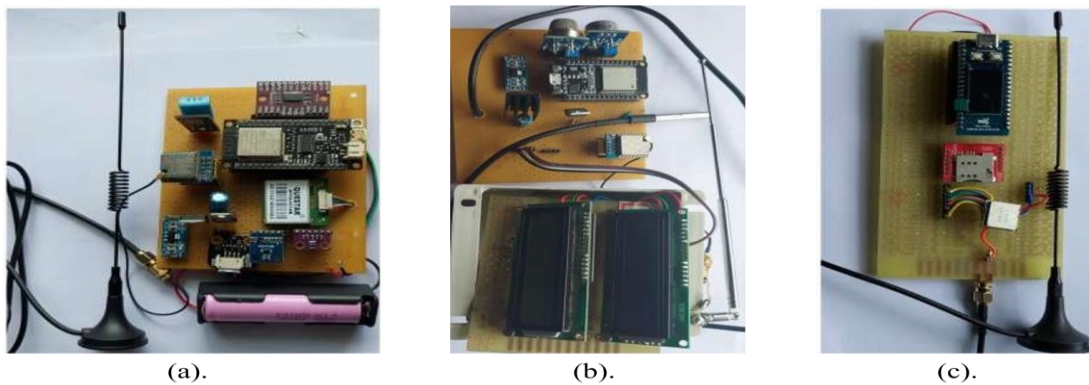


Fig. 8: (a). Hardware details of Battery-operated End node used in the experiment; (b). Hardware details of second End node used in the experiment; (c). Hardware details of Cluster Head used in the experiment

Table III: Battery Test Results

Packets Sent	Equivalent number of years	Battery voltage with load ON
Start		4.0/ (fully Charged)
43200	6.58	3.98



86400	13.15	3.85
129600	19.72	3.76
172800	26.30	3.67
216000	32.88	3.55
259200	39.45	3.41

TABLE IV: Received sensor values along with RSSI

Node 1(100 -meter range)			Node 2(500 -meter range)		
Parameters	Value	RSSI (dBm)	Parameters	Value	RSSI (dBm)
Ambient Temp	29.30 ⁰ C	-45	Solar Temp	28.44 ⁰	-62
Humidity	56 ⁰	-41	CO2(ppm)	402 ⁰	-63
Illumination	2302.1 ⁰	-43	CO(ppm)	0.44 ⁰	-60
Lattitude	13.03 ⁰	-45	NH4(ppm)	1.10 ⁰	-58
Longitude	77.64 ⁰	-44	Toluene(ppm)	0.08 ⁰	-62
Air Quality	87 ⁰	-41			

Node1 values

Parameter	Values	RSSI(dBm)
Latitude	13.03	-25
Longitude	77.64	-25
Ambient Temp	29.90	-26
Humidity(%)	46	-33
Light(lx)	2860.00	-30

Node2 values

Parameter	Values	RSSI(dBm)
Soil Temp	28.44	-82
CO2(ppm)	400.00	-63
CO(ppm)	0.44	-76
NH4(ppm)	1.10	-75
Acetone(ppm)	0.07	-75
Toluene(ppm)	0.08	-75

[Click here!](#) To check the location in Google maps

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Node1	Ambient_Temp	Humidity	Latitude	Longitude	Altitude	Illumination	Node2	Soil_Temp	CO2(ppm)	CO(ppm)	NH4(ppm)	Toluene(ppm)
2		27.42 °C	52%	13.03°	77.64°	927.80 mts	1598.24lx		27.12 °C	408	2.45	5.12	0.42
3		27.76 °C	52%	13.03°	77.64°	927.80 mts	1598.92lx		27.67 °C	403	3.12	5.7	0.36
4													

Fig. 9: Sensor readings published on Web Page as well as Google Spread Sheet.

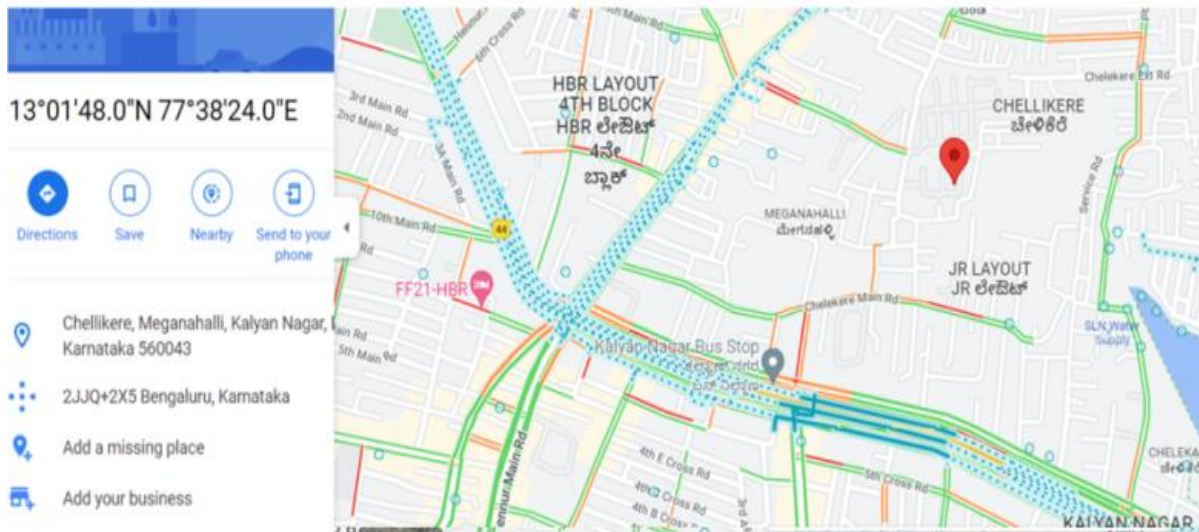


Fig.10 Node location on Google map

6. Conclusion

In this work, we mainly focused on the design of the end node and Cluster Head. An end node consisting of Semtech SX1276 LoRa module, ESP32-D2 microcontroller, BME280 sensor, DFRobot SGP40 air quality sensor, and BH1740 digital Light sensor is fabricated and tested using an outdoor antenna which is kept at a fixed location of about 100 meters from the Cluster Head. The second end node is also kept at a fixed location about 500 meters from the CH. The height of these end nodes is about 5 meters, whereas the CH Omni directional antenna is kept on top of the building at a height of 30 meters. The actual currents drawn from individual chips are measured using digital meters in different modes of operation. The time for which a particular mode is active also contributes to the battery life, therefore accurate measurements are required to determine the battery life. These timings are determined by measuring the execution time of codes used in the program. Also, we have kept the nodes and cluster head powered on continuously for six months to conclude that the 2200mAh battery used at the end node can last 35 years without recharging.

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