Design and Development of Waste Management System with Blockchain Technology and LoRa Network

A Thesis
Submitted in partial fulfillment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

in

Electronics & Communication Engineering

By

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PUNJAB
October 2021

DECLARATION

This thesis is an account of research undertaken between July 2018 and August 2021 at School of Electronics and Electrical Engineering, Lovely Professional University, Phagwara, India. Except where acknowledgement is the customary manner, the material presented in this thesis is, to the best of my knowledge, original and has not been submitted in whole or part of degree in any university.

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CERTIFICATE

This is to certify that the declaration statement made by the student is correct to the best of my knowledge and belief. He has submitted the Ph.D. thesis "**Design and Development of Waste Management System with Blockchain Technology and LoRa Network**" under my guidance. The present work is the result of his original investigation, effort and study. No part of the work has ever been submitted for any other degree at any University. The Ph.D. thesis is fit for the submission and fulfillment of the condition for the award of Ph.D. degree in Electronics and Communication Engineering from Lovely Professional University, Phagwara.

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ABSTRACT

According to United Nations, 66% of the global population will be living in urban cities by 2025. It also reports that the consumption of material worldwide will be accelerated to 90 billion tonnes by 2050, contrasted to 40 billion tonnes in 2010. The planning commission report (2014) India reveals that the waste generated is approximately 62 million tonnes (MT) per annum. It is projected that the population of India will be 1.82 billion by 2051, and the population of urban area will be 50% of the total population. Considering the rise in the population, the waste will be expanding by 5% per year. Therefore by 2047 the waste generated will be approximately 260 million tonnes per annum. In present scenario, only 70% of waste is collected in India and the remaining 30% gets amalgamated with other debris or lost in the environment. Only 12.45% of the garbage collected is treated, and the remaining is dumped in landfills which causes soil deterioration, groundwater contamination, and air pollution. Solid Waste Management is required for the collecting the solid waste generated by the individual residing in urban cities and also helps to achieve the sustainable environment by collecting, transporting, recycling and disposing the solid waste to reduce the harmful effects on the environment. The amount of the waste is overflowing in the bins due to delay in collection at appropriate time.

However, the information and communication technologies can have significant impact on the solid waste management. The information and communication technologies can provide a convenient way for addressing the waste management challenges. The Internet of Things is one of the most suited technologies for solid waste management because it provides for continual monitoring of bins from any remote area. As the bins are located in an outdoor environment, the sensor node of bins need battery to power up. The blockchain technology can also contribute to the solid waste management by establishing the secured and transparent business model for providing the economic

benefits to the individual from the waste. The primary aim of this thesis is to implement the Waste-to-Money model in the solid waste management with the assistance of blockchain technology and Long Range (LoRa) network. The waste generated in a community area is proposed to connect to the recycling unit through a cloud server to monitor the waste and gain the value in terms of money based on the amount of waste with blockchain technology.

To achieve the goal, the thesis is organized into four objectives. A customized hardware has been designed and developed for the bins to communicate the sensory data with the help of the LoRa communication protocol. The gateway is customized with and ESP 8266 Wi-Fi, and LoRa communication protocol. The LoRa protocol is employed to minimize the transmission cost, power consumption and enhances the transmission range for the bins. To establish LoRa network with the bins and gateway, a FLoRa simulation along with evaluation metrics like bit rate, time on air, receiver sensitivity, and link budget are performed. The simulation and evaluation metrics concludes the optimal parameters for the implementation of LoRa based system as Spreading factor 7, 125kHz of bandwidth and code rate 4. The LoRa spreading factor is a parameter that influences the spread out of data bits in an amount time and high spreading factor (i.e., 12) implies the more spread out of data bits in a time. The amount of Forward Error Correction added to LoRa packet is controlled by the LoRa code rate, higher code rate improves the reliability of connectivity during interference presence. Bandwidth denotes the amount of data transferred by LoRa communication in given time. A customized waste management server is implemented to visualize and monitor the status of the bins through internet. The waste management server has been designed to work with a lightweight blockchain that establish a waste-to-money model on basis of real-time sensor data. The integration of waste management server with lightweight blockchain is achieved with flask server and local network.

ACKNOWLEDGEMENT

"To begin, I want to express my gratitude and thanks to Almighty for showering his blessings and strengthening me from inside throughout my research work and allowing me to accomplish it successfully"

Firstly, I would like to express my sincere gratitude to my supervisors Dr. Rajesh Singh and Dr. Anita Gehlot for the persistent encouragement to my Ph.D. related research, and for their patience, motivation, and immense knowledge. This thesis was made possible due to the guidance of my supervisors, and I feel privilege for getting an opportunity to work with them.

I am grateful to my parents and family members for their kind blessings and encouragement to complete this research. Beside I would like to thank Mohammad Subhani, Yasir Afaq, Bharat Yadav, Prabin Kumar Das and Biswajyothi Roy for their valuable suggestions and assistance in my research. I would also like to thank Dr.Amit Kumar Thakur, Dr. Mamoon Rashid, Dr. Deepak Prashar, Prof. Dr.Osama S. Faragallah, Dr. Sultan S. Alshamrani, Dr. Ahmed Saeed AlGhamdi, Dr. Walid El-Shafai, and Dr. Mohammed A. AlZain for their valuable technical and financial assistance in the research.

I would like to take this opportunity to express my gratitude to entire family of Lovely Professional University, for their support and encouragement. I would like to thank the Division of Research and Development and School of Electronics & Electrical Engineering for all the support encouragement throughout the research work.

Date: 01/10/2021 Shaik Vaseem Akram

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LIST OF ABBREVATIONS

API	Application Programming Interface
BLE	Bluetooth Low Energy
BW	Bandwidth
CF	Carrier Frequency
CNN	Convolutional Neural Network
CR	Code Rate
CSS	Chirp Spread Spectrum
DSS	Decision Support System
E-waste	Electronic waste
FLoRa	Framework for LoRa
GSM	Global System for Mobile Communications
GPRS	Global Packet for Radio Service
GND	Ground
GUI	Graphical User Interface
ICSP	In Circuit Serial Programming
IoT	Internet of Things
IP	Internet Protocol
LCD	Liquid Crystal Display
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Network
MDLS	Multilayer Deep Learning System
MT	Million Tonnes
MEMS	Micro-Electro-Mechanical Systems
MQTT	Message Query Telemetry Transport
NB-IoT	Narrowband IoT

PAN	Personal Area Network
PoC	Proof-of-Capacity
PoW	Proof of Work (PoW),
PoA	Proof-of-Activity
PoB	Proof-of-Burn
PoS	Proof-of-Stake
QGIS	Quantum Geographic Information System
RFID	Radio-frequency Identification
SF	Spreading Factor
SNR	Signal-to-Noise Ratio
SPI	Serial Peripheral Interface
ToA	Time of Arrival
UNL	Unique Node Lists
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WC & T	Waste Collection and Transportation

“*This Thesis Work is Truly and Heartfully Dedicated to My Parents for their Inspiration and Motivation Behind My Success*”

Chapter 1

Introduction

In this chapter, the overview of solid waste management is presented in detail along with the significance of solid waste management and the impact of information and communication technologies in solid waste management. This chapter also presents the motivation, research objectives, and thesis organization.

1.1 Solid Waste

Solid waste is unusable solid material generated by human activities in residential, industrial, or commercial sites. It is generated either from the product of manufacturing processes or as a result of things or materials being disposed of after consumption in the domestic or commercial domains. Figure 1.1 illustrates distinct kinds of solid waste categorized based on hazardous and non-hazardous. Organic waste, agriculture waste, and plastic waste fall under non-hazardous waste. The composition of waste is vital for implementing waste management life cycles like collection, transportation, recycling, and disposal (Bisinella et al., 2017). It also plays a crucial role in greenhouse gas emissions (Ramachandra et al., 2018). Industrial waste, E-waste, nuclear waste, and bio-medical waste are hazardous waste.

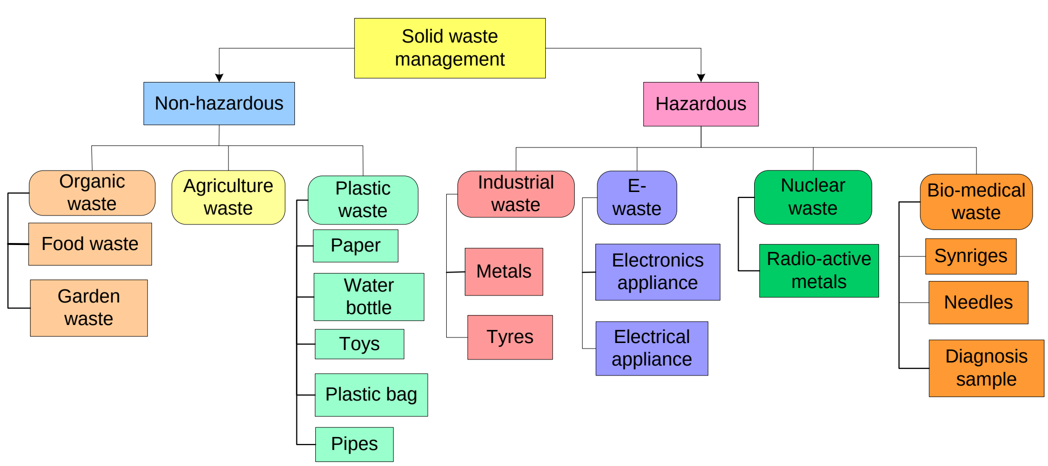

Figure 1.1 Types of Solid Waste

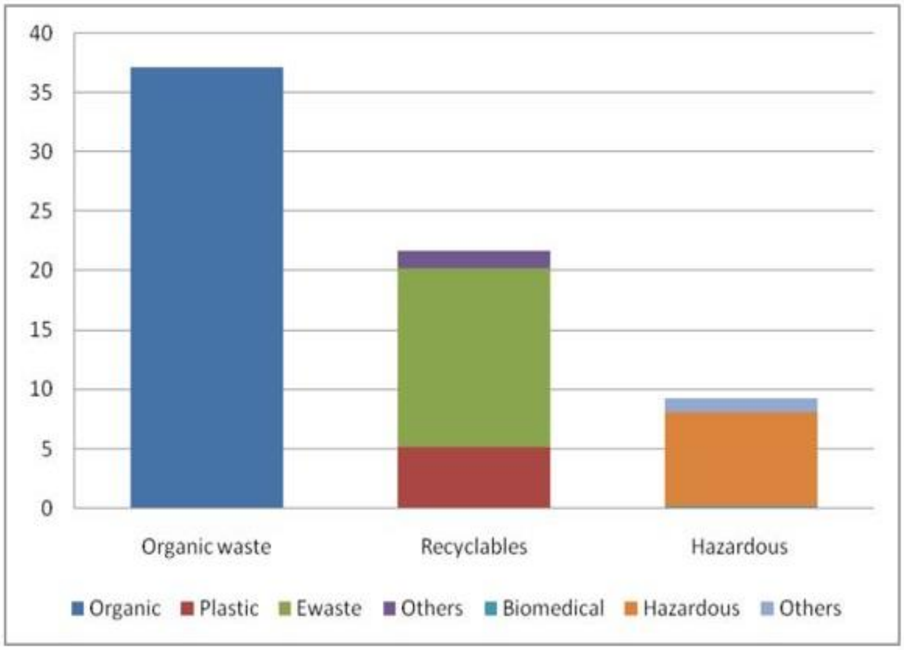

Figure 1.2 Composition Of Solid Waste in India (*'Solid Waste Management Rules Revised After 16 Years; Rules Now Extend to Urban and Industrial Areas': Javadekar*, n.d.)

The waste composition differs from one country to another country and from one municipality to another municipality, urbanization, income level, and government regulations (Abdel-Shafy & Mansour, 2018)(Nagpure, 2019). According to the press information bureau, 2016 (*How Can India's Waste Problem See a Systemic Change? | Economic and Political Weekly*, n.d.), the composition of India's waste. The waste's composition is classified into three categories: recyclable waste, organic waste, and hazardous waste. Organic waste comprises of food, paper, wood, etc. Organic waste is the highest generating waste in India (Figure 1.2), electronic waste (E-waste) and plastic waste are categorized as recyclable waste. Organic waste is waste generated from the residents and food restaurants (Kawai & Huong, 2017). Organic waste from the residents and food restaurants is managed by the local municipal body. Recyclable waste is waste, in which the waste is transformed into new material. Hazardous waste is a waste that has the properties of causing damage to human health or the atmosphere. Hazardous waste is produced from the industrial manufacturing process of waste to battery trash, or it can take several forms, including liquids, and liquid gases (Saleh, 2016). Biomedical is waste from the hospital environment like syringes, needles, diagnosis samples, drugs, medical devices, etc. This waste is infectious and can spread infectious diseases (Datta et al., 2018). Ineffectual supervision of organic waste results in the creation of airborne disease in an open environment leads to contamination of water bodies and generates harmful gases due to burning (Ayilara et al., 2020) (Rajendran et al., 2013).

Solid Waste Management is required to achieve sustainable metropolitan development by collecting, transporting, and recycling the solid waste in advance for minimizing the harmful effects on the environment and humans (*THE 17 GOALS | Sustainable Development*, n.d.). The waste management process comprises the collection, transportation, and deployment of different bins for disposing of waste and transportation (figure 1.3). Recycling is the process of turning waste material into usable material.

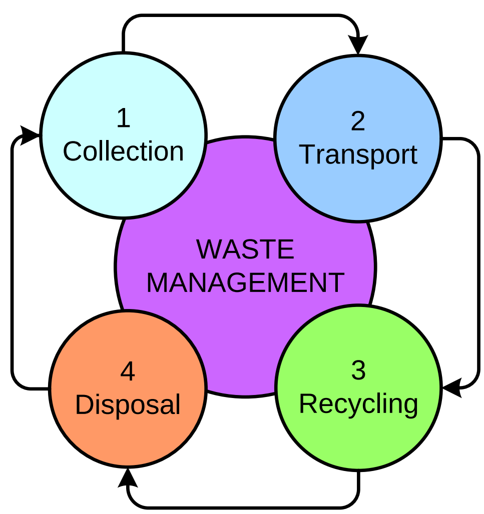

Figure 1.3 Activities of Waste Management

According to United Nations, 66% of the global population will be living in urban cities by 2025 in comparison to 54% currently inhabiting urban cities. It also reports that the consumption of material in cities will be accelerated to nearly 90 billion tonnes by 2050, contrasted to 40 billion tonnes in 2010 (*The Weight of Cities | Resource Panel*, n.d.).

According to World Bank research [14], 4.3 billion urban inhabitants will generate 2.2 billion tonnes of solid trash annually by 2025. The report reveals that high-income people are generating a large quantity of waste than low-income. The Indian planning commission report reveals that in 2014 the waste generated by India was 62 MT. It is projected, by the year 2051 the population of India will be 1.82 billion and the population of urban India will reach nearly 50% of the total population (*Planning Commission Report. (2014). Reports of the taskforce on waste to energy (Vol-I) (Retrieved from http://planningcommission.nic.in/reports/genrep/rep_wte1205.pdf - Google Search*, n.d.). Considering the rise in the population, the waste will be increasing by 5% per year. Therefore by 2047, the waste generated will be around 260 million tonnes per annum. To dump this amount of waste, around 1400 Sq. Km area will be required (On, 2009).

In India, only 70% of waste is collected, and the remaining 30% gets amalgamated with other debris or lost in the environment. Only 12.45% of the garbage collected is managed, and the remaining is dumped in landfills, causing soil deterioration, groundwater contamination, and air pollution. Urban local bodies in our country spend more than 70% of their budget only for collecting waste and the remaining amount 30% is utilized for transport (Kumar et al., 2017b). The challenges for solid waste management indicate the immediate need for necessary action for upgrading the services of waste management authorities, especially in the middle & low-income countries (Cheng & Hu, 2010). The authorities are confronted with the challenges in optimizing the routing path of solid waste which has a direct impact on operational cost, collection efficiencies, and pollutant emissions (Tsai et al., 2020). Many studies have been undertaken for capacitated vehicle routing problems to minimize pollutant emissions and cost (Guerrero et al., 2013) (Singh, 2012). Yet many investigations are considering only static data instead of real-time for routing optimization. To solve the growing problems in solid waste management, information and communication technologies can play a vital role due to the increasing need for automation in data processing, identification, connectivity, storage, computation demand, and analysis (Anagnostopoulos et al., 2017).

1.2 Technology in the Solid Waste Management

Information and communication technology is widely recognized in data collection, processing, and communicating required information for the (*OECD Glossary of Statistical Terms - Information, Communication Technology (ICT) goods Definition*, n.d.). This technology provides a convenient way for addressing solid waste management issues due to its ability to enable access to information instantly from any remote location (J.-W. Lu et al., 2013). An evident incentive for achieving the broad solid waste management objectives would be achieving sustainable urban development. Even in the paradigm of smart cities, technologies are being used for the establishment, enactment, and empowerment of a sustainable growth environment (J. Wu et al., 2018). The Information of technologies is becoming more and more critical because of the increasing demands on acquisition, dissemination, and interpretation of big data along with fast computing capabilities to achieve the goals of intelligent solid waste management systems. Innovations in Micro-Electro-Mechanical Systems (MEMS) technology have encouraged to build of systems for solid waste management during the past few decades (Lyshevski, 2018), and literature shows the capability of tackling the distinct issues of solid waste management in terms of environment, operational cost, and time (J. W. Lu et al., 2013).

The site selection was in previous schemes performed without adequate preparation for waste bin, dumping point, recycling station, or collection point. The waste collection was undertaken without a proper route plan by drivers. It causes ineffective collection as bins may be filled or empty which also increases the transport cost due to repeated visiting for partial waste collection. The technologies may be applied for resolving the issues in solid waste management, although it is difficult to follow the appropriate combination of technologies for establishing an effective system. Technologies in solid waste management provide an opportunity for establishing monitoring activities in remote areas. In later time the different Information and communication technologies that have already been incorporated into the solid waste management for monitoring the bins, identifying the location of the bins, route optimization, real-time monitoring of the bins, and extracting the information

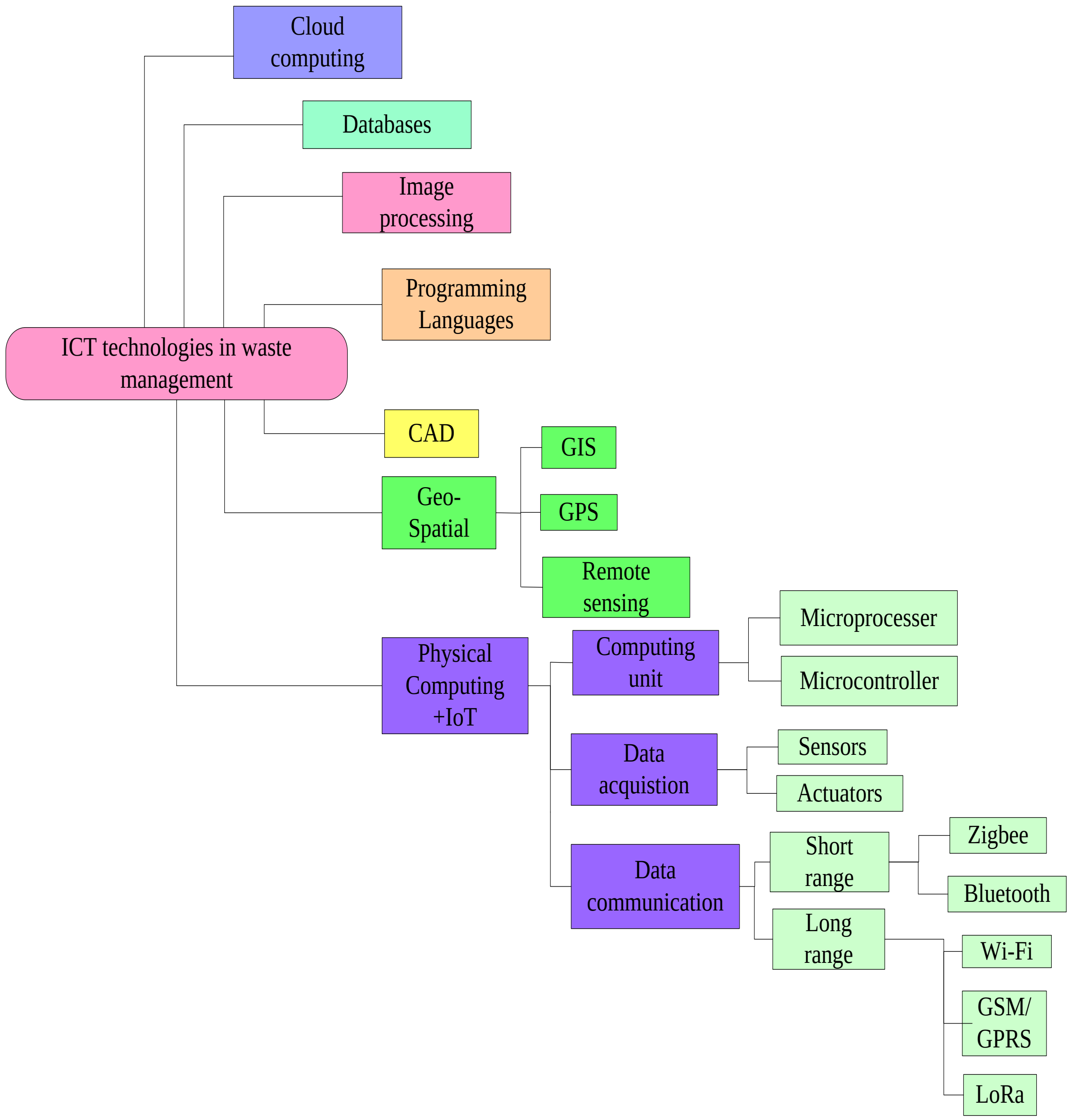

Figure 1.4 Technologies in Solid Waste Management

Technologies are classified into three types, concerning the parameters like spatial data, data acquisition, and data communication. Information and communication technology is classified into four types: spatial technologies, data acquisition technologies, data communication technologies, and IoT (figure 1.4). Most of the system uses the integratlion of two or more technologies. This section discusses the Information and communication technologies that are implemented in solid waste management for supervising, collecting, and management.

1.2.1 Geospatial Technologies

Geographical information systems, remote sensing, and Geopositioning system are the geo-spatial technologies used for route optimization, dumping site selection, and waste generation information (Milla et al., n.d.). Geospatial technology facilitates obtaining data about the earth. This technology may be used to make intelligent decisions from the maps and models to acquire the desired result. Geospatial technology can track each event during trucks transportation concerning the change in the surface of the earth. Geographical information system, remote sensing, and Geopositioning system are three Geospatial technologies which are being implemented in the solid waste management system. It is important to allocate and utilize resources efficiently which can be achieved by using emerging technologies such as geographic information systems, remote sensing, and mathematical optimization approaches (Dutta & Goel, 2017b). Remote sensing is utilized for monitoring and analyzing the physical attributes of an area (Nishanth et al., 2010). Remote sensing can be employed for the environmental assessment of the water bodies. It can be utilized for landfill sites regarding water bodies pollution due to the decomposition of mixed waste in the land. It can also be integrated to estimate the waste generation and identify the appropriate site for constructing landfills for waste disposal. The integration of Geographical information system, with remote sensing, and Geopositioning system is processed to obtain spatial data and its analysis (Chalkias & Lasaridi, 2009).

The geographic information systems are used in solid waste management for a range of solutions including site selection for waste management disposal facilities, and management of waste collection and transportation (WC&T) (Ghose et al., 2006b). It is also employed for identifying recycling drop-off centers (Chang et al., 1997), optimizing solid waste management in coastal areas, and assessing solid waste generation rates using local demographic and socioeconomic data (Vijay et al., 2008). Decision-makers can be optimized for solid waste management by employing remote sensing in conjunction with Geographical information systems. It may improve efficacy and increase profitable returns or savings. Site selection (Ghose et al., 2006a; Karimi et al., 2019; Mussa & Suryabhagavan, 2019; Singh, 2019), route optimization (Akhtar et al., 2017; Hannan et al., 2018; Vu et al., 2019, 2020), bin location selection (Erfani et al., 2017; Farahbakhsh & Forghani, 2019; D. Khan & Samadder, 2016; Rathore et al., 2020), waste generation estimation (Solano Meza et al., 2020) are achieved by Geographical information system. Vehicle tracking (Kariapper et al., 2019), route scheduling (F. I. Khan & Gawade, 2018), driver tracking (Kariapper et al., 2019), collection monitoring (Chakole et al., 2017; Steyn & Willemse, 2018; Tarone et al., 2018) are the activities that are possible with the Geopositioning system. Environment assessment and environment feature monitoring are achieved with the assistance of remote sensing (*Remote Sensing: Models and Methods for Image Processing* - *Robert A. Schowengerdt* - *Google Books*, n.d.).

Global positioning systems track the object based on longitude and latitude. In solid waste management, a global positioning system can be combined with a geographic information system and Radio Frequency Identification (RFID) for tracking the trucks and drivers during the waste collection and optimization of the routes. Global positioning system and Geographic information system support landfill selection and assessment of waste management. Remote sensing can be used for monitoring and analyzing the physical attributes of an area. Remote sensing can also be used to measure the environmental impact of aquatic bodies and landfill sites for measuring the amount of water polluted by the decomposition of mixed trash on the land. Remote sensing can also be integrated for estimating waste generation and identifying the appropriate site for constructing landfills for waste disposal.

1.2.2 Data Acquisition Technologies

Data acquisition technology can acquire real-time information about physical things without human intervention. Availability of real-time information can encourage the authorities to track and monitor bins continuously (Faccio et al., 2011). Real-time information can also assist in evaluating the generation pattern and quantity of waste in the bins. It can facilitate the trucks for collecting the waste at an appropriate time for avoiding the overflow (Fraden, 2004), (Cavdar et al., 2016a). Data acquisition technology includes i) sensors and ii) Imaging technology. Sensors acquire the chemical, physical and biological properties of any material and convert it into an electrical signal. In many studies, researchers have addressed the significance of the sensor in solid waste management for real-time quantity & weight of waste and emission of the gas from the garbage. Imaging technology is another data acquisition technology that can be implemented in solid waste management for capturing and monitoring the visuals of the bins and the surrounding environment. Camera and video surveillance (J. Huang et al., 2010), (Sundas & Panda, 2020) are the sources of image technologies to capture the digital images for the prediction of possible events. Bin level detection (Arebey et al., 2010; J. Huang et al., 2010; Wagland et al., 2012), waste sorting (Gundupalli et al., 2017; Liu et al., 2018; Nagori et al., 2019; Thanawala et al., 2020; Vo et al., 2019), and collection monitoring are a few applications of imaging technology. The visuals which are captured by the camera are beneficial for analyzing the waste generation pattern and other activities with the assistance of artificial intelligence (AI) techniques. Multilayer Deep Learning System (MDLS) model can also be applied to the images for classifying the waste (Chu et al., 2018).

1.2.3 Wireless Communication Technologies

Wireless communication technologies in solid waste management use data transmission and geo-spatial data for stable and reliable interconnection with the bins. The advent of communication technologies opens opportunities for transmitting information from a remote location (Hannan et al., 2015a). The wireless communication technologies are categorized on the basis of transmission range likely, i) Long-range communication, ii) Short-range communication. LoRa is a long-range communication technology. Zigbee Bluetooth and Wi-Fi, (Misra et al., 2018) are short-range wireless. Global system for mobile communication (GSM) / global packet for radio service (GPRS) is long-range communication that operates on the frequency band of 900-1800 MHz (Jawad et al., 2017). However, the major drawback of the GSM/GPRS is the high-power consumption.

Table 1.1 Wireless Communication Technologies in Solid Waste Management

Parameter/ Technology	**GPRS/ GSM**	**LoRa**	**Zigbee**	**Bluetooth**	**Wi-Fi**
Network	Wide area network (WAN)	Low power wide area network (LPWAN)	Personal Area Network (PAN)	Personal Area Network (PAN)	Local Area Network (LAN)
Operating band	900–1800 MHz	433/869/915 MHz	2.4 GHz 868 and 915 MHz	2.4 GHz	2.4 GHz /5 GHz
Modulation type	GMSK/ QPSK	GFSK	OQPSK/ BPSK	DPSK, GFSK, and DQPSK	OQPSK/ BPSK
Security type	GEA, MS-SGSN, MS-host	Advanced Encryption System -128b	128-bit Advanced Encryption System	64- or 128-bit Advanced Encryption System	128 bits Advanced Encryption System
Bandwidth	200 kHz	Less than 500 kHz	2 MHz	1 MHz	22 MHz
Topology	Cellular	Star to star	Mesh, peer2peer, star, mesh	Scatternet	Point to hub
Transmission range	1-10km	5-10km	100 m	10-50 m	100 m
Research	(Hannan et al., 2011), (Cavdar et al., 2016a), (Deka et al., 2018),(Sohag	(Addabbo et al., 2019), (Cerchecci et al., 2018a; Lozano, Caridad, De	(Karthikeyan et al., 2017), (Reis et al., 2015), (Aswin Raaju et al., 2019)	(Misra et al., 2018), (Memon, Shaikh, et al., 2019), (S. T.	(Rahman et al., 2020)

	& Podder, 2020) (Singhvi et al., 2019)	Paz, Villarrubia Gonzalez, et al., 2018; Sheng et al., 2020; Ziouzios & Dasygenis, 2019)		Wilson et al., 2019)	

The limitations of high power can be overtaken by the LoRa, as it is communication is low power and long-range module to transmit the sensory information up to 5 km (urban) and 10 km (Rural). Bluetooth is a wireless PAN (WPAN) communication protocol that communicates information with low power consumption. Wi-Fi is a wireless LAN (WLAN) which communicates information over Internet Protocol (IP). Table 1.1 shows the detailed review of wireless data communication technologies in solid waste management. It is concluded among wireless technologies, that LoRa (Long Range) is the promising and reliable communication technology to meet the transmission requirements of solid waste management. The end devices are powered with a battery, and GSM/ GPRS, Wi-Fi consumes the high power for the data transmission. Zigbee and Bluetooth consume low power however these two technologies only can transmit to the range of 100m. LoRa (Long Range) is the optimal technology that dissipates low power with the reliable long-range transmission with security.

1.2.4 Long-Range Communication

Wireless technology will connect more than twenty-five billion people by 2020 (Sinha et al., 2017). LPWAN (Low Power Wide Area Network) technologies are performing a vital role in communication as it supports long-range with minimal power consumption. LoRa, Sigfox, and NB-IoT are the LPWAN technologies for supporting the requirements of wireless communication (Table 1.2). LoRa is a robust low-power wireless networking that is used for transmitting data long-distance. LoRa works on modulation of the chirp spread spectrum (CSS) to modulate ISM (Industrial, Scientific & Medical) signals (H. C.

Lee & Ke, 2018). CSS modulation allows a narrow band signal to be sent over a wider channel bandwidth. LoRa operates on ISM 868 MHz (Europe), 995 MHz (North America), and 433 MHz (Asia)(Mekki et al., 2019). In rural areas, LoRa can communicate between 10 and 40 kilometers, while in urban areas coverage is 1 to 5 kilometers. In a mesh network and cellular network, the nodes must wake up to synchronize with the network and check the messages. This mechanism increases the lifetime of a battery due to less energy consumption. LoRa is integrated with a pure ALOHA mechanism, and this makes the network wake up automatically when there is a requirement of transmitting the data. This factor enables LoRa communication to consume minimal power during the data transmission.

Table 1.2 LPWAN Technologies [24]

Characteristics	**Technology**		
	LoRa	**Sigfox**	**NB-IoT**
Modulation	Chirp Spread Spectrum	BPSK	QPSK
Spectrum band	433/868/780/ 915MHz (Unlicensed ISM band)	868/902 MHz (Unlicensed ISM band)	Licensed LTE bands
Data rate	50 kbps	100 bps	200 kbps
Two-way communication	Half-duplex	Half-duplex (limited)	Half-duplex
Connectivity Range	5 km -20 km	10 km-40km	1km-10km)
Interference resistance	Maximum	Maximum	Minimum

1.3 Internet of Things for Solid Waste Management

IoT is the network of networks with the components of data collection, processing, and communicating to provide an ecosystem in which intelligent services are given to end-users (Asghari et al., 2019), (Madakam et al., 2015). The applications of IoT in the supply chain are timely planning, control, and coordination of supply chain processes by enabling agility, visibility, tracking, and information sharing (Ben-Daya et al., 2019). IoT has primarily 3-layer architecture (Sethi & Sarangi, 2017) including application layer, network layer, and perception layer (figure 1.5). The perception layer consists of sensors, which sense a change in the physical environment. In IoT, sensor technology plays a crucial part in monitoring physical objects/things. The network layer allows sensor data to be transmitted and processed through networks. The application layer provides application-related services to the end-user and defines different applications in which the IoT can be deployed. IoT can connect the bins to the internet for real-time monitoring and visualizing the status of the bins from any remote location. Wireless communication technologies like GSM, Zigbee, cdma2000 ev-do, and RFID are being integrated for establishing the interconnection between bins and servers. Moreover, node MCU and RKI-1451 have been implemented for communicating sensory data over the internet.

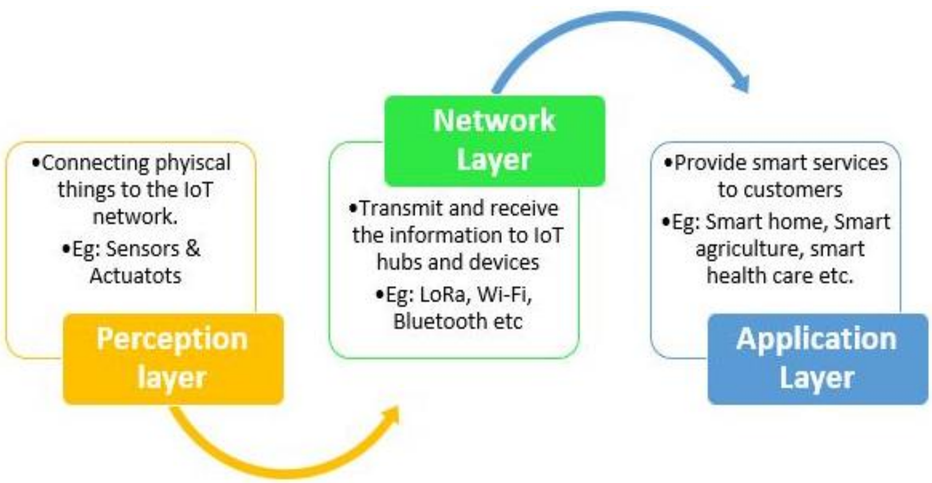

Figure 1.5 Basic Architecture of IoT

1.4 Blockchain Technology

Blockchain is a decentralized network that maintains an immutable and transparent record of transactional ledgers (Chen et al., 2018). Blockchain ensures complete decentralization by not depending on a third party, and intermediary (Monrat et al., 2019).

The blockchain technology is introduced by Satoshi Nakamoto in 2008 was only limited to a digital currency, i.e., bitcoin (*Bitcoin: A Peer-to-Peer Electronic Cash System*, n.d.). The unique features of the blockchain technology-empowered to implement widely in various industries for enhancing security and transparency. This technology consists of a cryptographical hash function (Baygin et al., 2019), and a record of time-stamped authorized blocks that are interconnected to the chain. Every block contains the hash of the previous block. The relationship between blocks is created, and a chain of blocks is created as shown in figure 1.6.

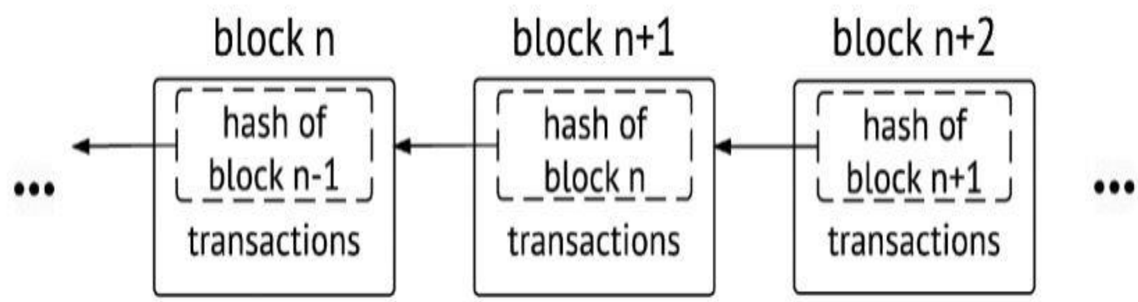

Figure 1.6 Blockchain Technology

The blockchain has gained a lot of interest because of its distinctive features as shown in figure 1.7. In the blockchain, decentralization implies that data is distributed to all network participants. Instead of allowing people to verify their identities before starting with a transaction, this technology encourages them to trust one another. Blockchain enhances transparency during transactions as the transaction ledger copy is available to everyone in the network. Privacy in the blockchain is protected by distributing the required details with the confidence of not misusing the information. Individuals can establish private networks with confined access and select from a list of companies linked to the blockchain network to secure transactions and identities. Since each block is linked to a public-key cryptography framework, blockchain technology has a strong security feature. The public key cryptography framework is made up of two keys: a private key, and a public key. Using asymmetric encryption, two keys can be used to verify the legitimacy of transactions.

The public keys can be shared with other entities during the transaction between the two entities, but the private keys are kept secret.

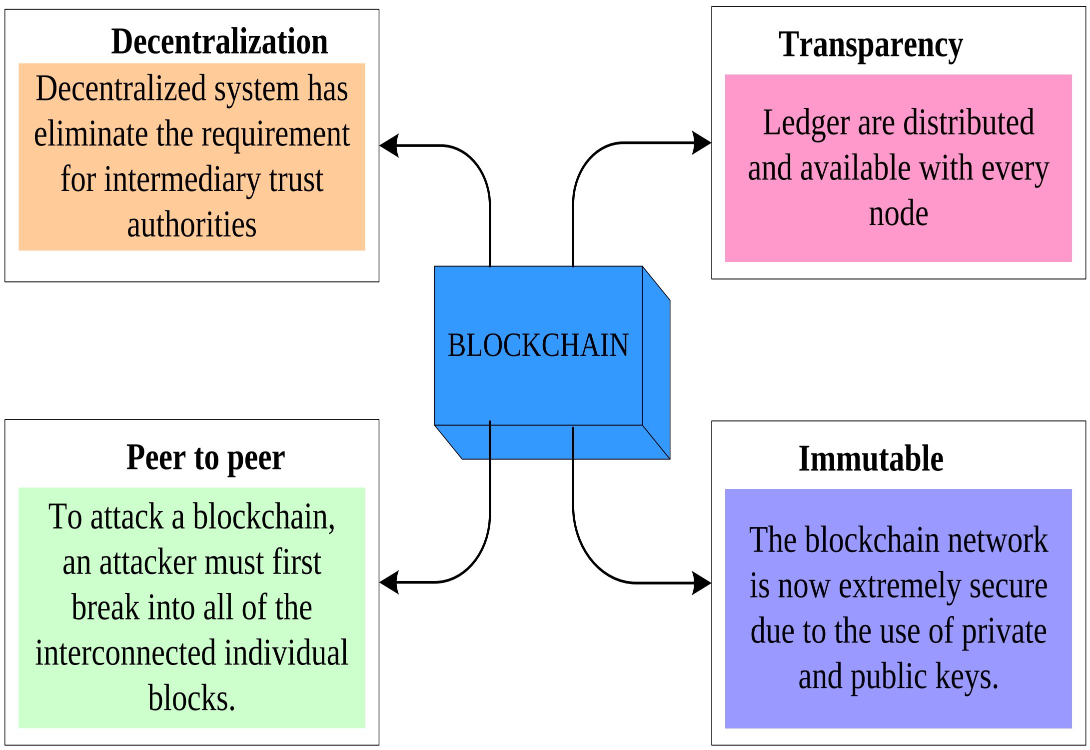

Figure 1.7 Blockchain Features (Naheed et al., 2021)

1.4.1 Consensus Mechanism

A consensus mechanism in blockchain systems is a fault-tolerant mechanism utilized to acquire a legal contract for an individual data characteristic. This mechanism is designed to resolve the challenge of 51% attacks on the blockchain network. A 51% attack is one in which a set of miners controls more than half of the network's resources. Consensus mechanisms such as Proof-of-Work (PoW), Proof-of-Stake (PoS), Proof-of-Capacity (PoC), Proof-of-Burn (PoB), Delegated Byzantine Fault Tolerance (dBFT), Proof-of-Activity (PoA), Unique Node Lists (UNL), SIEVE, Proof-of-Weight (PoW), and Practical Byzantine Fault Tolerance (pBFT) are implemented in various blockchain networks (K Christidis & Devetsikiotis, 2016).

1.4.2 Blockchain Architecture

The architecture of Blockchain uses a framework like Python, SQLite, and RESTful application programming interface (API). Data is encrypted using the authorized user's private key before it is uploaded to Blockchain Database API. With the assistance of Blockchain Database API, the data is decrypted using the user's private key. Blockchain Database API generates the hash value with a nonce (random string) in the event of an unauthorized update.

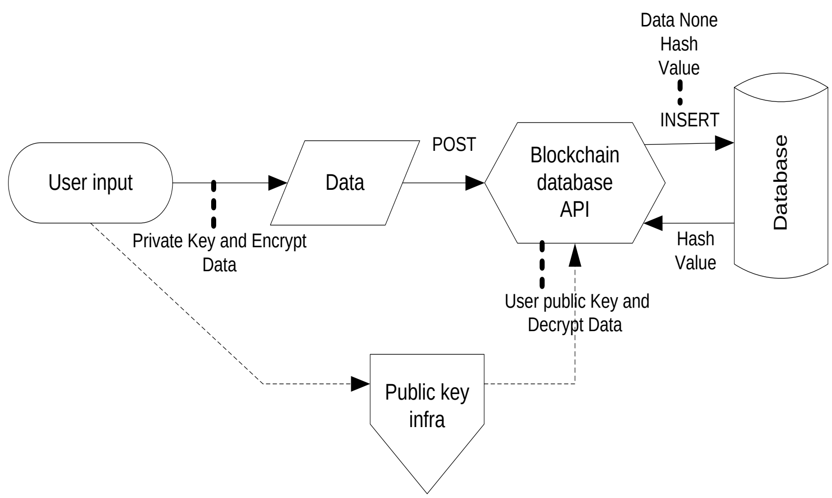

Figure 1.8 Blockchain Database Architecture

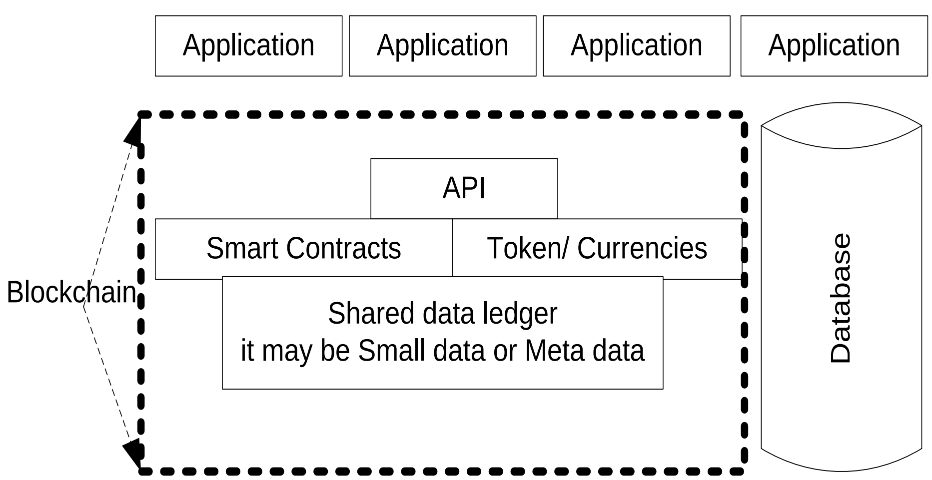

Figure 1.9 Blockchain used in Web Application

This was previously utilized for user authentication. If the changes occurred, the API can be notified, and this is how the data integrity will be ensured. Figure 1.8 and Figure 1.9 presents the database architecture of blockchain and blockchain mechanisms in web applications. The system's quality such as security, privacy, scalability, and sustainability are preserved by using the Blockchain as a software connector to build important architectural decisions apparently. Blockchain is used as a software connector including design trade-offs for quality attributes (X. Xu et al., n.d.).

1.5 Motivation

Solid waste management is very important in urban cities for maintaining a clean and green environment. The report of the United Nations and Environment ministry reveals the amount of the collected solid waste needs to be managed properly for avoiding the harmful effect on the environment and humans. Many researchers have implemented distinct techniques for tackling solid waste. The waste in the bins is still overflowing due to the delay in collecting the waste at an appropriate time. IoT can be used to monitor the bins through internet connectivity from any remote location. The integration of sensors with IoT makes identification of filled and alerting the garbage collector to collect the waste smoothly. The amalgamation of blockchain and IoT can accelerate business models by handling transaction and data authenticity, at the same time. IoT can become a point of connection with the real world and also connecting IoT to a decentralized network can help obtain real-time data and provide real-time waste tracking.

1.6 Research Objectives

The aim of this research is to implement a waste-to-money model in solid waste management. The four objectives of the research are as follows:

1. To design sensor node for the bins with communication capability.
2. To establish LoRa network between the bins.
3. Development of waste management server.
4. Integration of lightweight blockchain server with waste management server.

1.7 Thesis Organization

The organization of the thesis includes a total of seven chapters.

Chapter 2 covers the review of the literature of existing studies on solid waste management. The review of the literature concludes with the research gap from the previous literature.

Chapter 3 covers the system architecture and hardware development. The complete working of the system architecture along with the block diagram is discussed. The description of components selected for the sensor node and gateway is also discussed along with the Proteus Simulation model. The significance of hardware customization of sensor nodes and gateway are presented along with circuit diagram and PCB design.

Chapter 4 covers the performance analysis of the LoRa network to evaluate the optimal parameters which are required for the system implementation using LoRa. The significance of performance analysis and the explanation of distinct network parameters of the LoRa are discussed. A FLoRa simulation is performed for calculating the energy consumption of nodes by varying parameters like spreading factor (SF), Bandwidth (BW), transmission (Tx) power, number of nodes, and number of gateways with a carrier frequency (CF) of 433 MHz. The bit rate, time on-air (ToA), link budget, receiver sensitivity, and battery life of sensor node based on LoRa are evaluated by varying parameters like code rate (CR), BW, SF, Tx power, and payload size.

Chapter 5 covers the development of the cloud server for waste management application. The significance of the integrating cloud server with the customized gateway and sensor node is described. The customized gateway and sensor node interconnected with the blynk server and Thingspeak server through Wi-Fi and API are discussed. The development of the customized cloud server based on Mongo database, Node.js, and Angular framework is demonstrated.

Chapter 6 covers the integration of the blockchain with the waste management server for implementing the waste-to-money model. The significance of integrating blockchain with waste management server is also addressed. The architecture and implementation of the blockchain with waste management server through local API are presented in detail.

Chapter 7 concludes the thesis by highlighting the prime outcomes of the current research and the significant contribution of the thesis. The scope for future research in this area is also discussed.

1.8 Chapter Summary

In this chapter, the background of solid waste management is presented with motivation. The role of information and communication technologies in solid waste management is discussed including geo-spatial, wireless data acquisition, and wireless data communication technologies. Moreover, the significance of IoT, LoRa, and blockchain technology is presented with the motivation of the study. The objectives and thesis organization of the research work are discussed in this chapter.

Chapter 2

Review of Literature

In this chapter, the review of literature on solid waste management is discussed to study the existing technologies. The review of the literature concludes with the research gap from the previous literature.

Solid waste management is a utility that every municipality provides to its residents. It is probably the most important municipal facility and a requirement for complex municipal services such as transportation, health, or education (Rajendran et al., 2013). Due to urbanization and a wide amount of waste generation, the static methods implemented in solid waste management are limited to overcome the challenges. On other hand, Information & Communication Technology (ICTs) gained attention and is capable of handling the challenges of solid waste management due to the increased demand for automated data collecting, identification, storage, communication, and analysis in conjunction with fast and equivalent processing (Johansson, 2006; McLeod et al., 2013a). ICTs could also help in addressing various limitations such as site selection, collection monitoring, intelligent recycling, and inefficient waste disposal (Hannan et al., 2015b). With the same, in this chapter, the literature is carried out on the different ICTs technologies which are implemented in solid waste management.

2.1 Spatial Technologies in Solid Waste Management

In early-stage monitoring of solid waste, geo-spatial technologies are widely implemented with RFID. The RFID is integrated with GSM, geographic positioning system & GIS to monitor the solid waste bin and the truck (Hannan et al., 2011). Geographic Information System -based DSS was implemented for enhancing the recycling management along with collection optimization and results concluded that the collection was 2.5 times more effective than the existing collection method (Anghinolfi et al., 2013). Geographic Information System analysis is integrated with an Agent-based model and equation-based to optimize the transportation of waste collection (Nguyen-Trong et al., 2017). The performance of the model is evaluated by a case study in Hagiang city of Vietnam. The result shows that the proposed model can reduce the cost of waste collection by 11.3%. Geographic Information System -aided model is implemented for proper allocation of solid waste bins in Dhanbad city (D. Khan & Samadder, 2016) and the vehicle route problem solver is also utilized for better optimization of routes for the trucks. Table 2.1 illustrates the literature for the Geographical information system in solid waste management. The studies majorly focused on route optimization. For route optimization, the Geographical information system is integrating with namely agent-based, and equation-based, 3D-based, DSS, and dual-phase modes.

The amalgamation of the Geographical information system with the aforementioned models is implemented for achieving an efficient optical path during the waste collection. It is also integrated with fuzzy logic, remote sensing for site selection, and placement of the bins. Arc geographic information system tool is employed for allotment of bin & route optimization. Quantum Geographic information system is useful for estimating the amount of waste generation at a particular site. A geographical information system can assist the municipal authorities with the proper operation of the waste collection system and disposal unit. The utilization of geographic positioning systems in association with other communication and spatial technologies, particularly geographic information systems, aids in tracking the vehicles and garbage bins for monitoring position and collection time.

A framework is created with a geographic positioning system and other traceability technology to optimize the collection of solid waste in terms of routing and costs(Faccio et al., 2011). Bins are equipped with perception technologies, and the truck is equipped with a GPRS module, weighing system, geographic positioning system receiver, RFID receiver, and a mobile laptop loaded with vehicle trackable applications. The control server retrieves data from bins and truck locations from the GPRS/geographic positioning system network.

The central DB stores position of bins on local maps, which are accessible by the geographic information subsystem and routing sub-modules (Abdallah et al., 2019).

Table 2.1 Geographic Information System in Solid Waste Management

Ref	**Spatial Technology**	**Function**	**Limitations**
(Anghinolfi et al., 2013), (Tavares et al., 2009)	Geographic information system	Selection of an optimal route for waste collection.	Require a high skilled person for implementing this system
(Nguyen-Trong et al., 2017)	Geographic information system-based Agent & equation- model	Optimizing the route for the waste collection.	This study is focused on the collection time, travel time and travel distance.
(Lotfi et al., 2007)	Integration of Geographic information system and fuzzy logic	Selecting the landfill site	Require a high processing unit for the implementation
(Fan et al., 2010)	Geographic information system-based DSS	Optimization and scheduling of route for collection of solid waste	Reducing the fuel cost also depends upon the type of the vehicles and roads.
(Kumar et al., 2017a)	Geographic information system-based spatial analysis	Evaluation of groundwater contamination	It is difficult to schedule a waste collection as the amount of waste disposed in the bins is not estimated.
(J. Lin et al., 2017)	Geographic information system-based spatial	Estimation of waste generation in an urban environment	Limited for assessment of groundwater and monitoring the other parameters in landfill sites are lacking.
(Vu et al., 2018)	Dual-phase Geographic information system model	Enhancing the waste collection route	Ineffective in recognizing the situation with the lowest system cost

(Okot et al., 2019)	Geographic information system and remote sensing	Selecting the appropriate for waste disposal.	Long term solid waste management plans should be presented, for valorizing the circular economy
(Imran et al., 2020)	Quantum Geographic information system	Predictive analysis & Quantum Geographic information systems are used for evaluating waste generation.	Creating an optimal route for the garbage truck with descriptive and predictive analysis.
(Town et al., 2020) (Amal et al., 2020)	Geographic information system	Analysis of the Geographic information system data for selecting the disposal site	The manual analysis also is integrated with a geographic information system for the effective selection of disposal sites.

The well-defined architecture for enabling traceability and monitoring, and the suggested dynamic scheduling and routing models, are among the strengths of the geographic positioning system (Ahmed et al., 2006). However, it's doesn't support a wireless sensor network for additional sensor data and GPRS fusion in all bins, which increases operational expenses.

Table 2.2 provides a review of solid waste management systems that are primarily based on geographic positioning system technology. As indicated in the table, geographic positioning system-based solid waste management systems are generally utilized in collection truck monitoring to record the time spent in trash transfer stations by vehicles (J. A. Lee & Thomas, 2004) (B. G. Wilson & Vincent, 2008). Other geographic positioning system applications in solid waste management concentrated on optimization of route based on static data (Flora, 2009), for collection monitoring (Arebey et al., 2011) as well as the implementation of efficient pricing.

Table 2.2 Geographic Positioning System in Solid Waste Management

Ref	Spatial technology	Function	Limitations
(Apaydin & Gonullu, 2007)	Global positioning system & Geographic information system	Integration of Global positioning system & Geographic information system for optimizing routes for waste collection.	Real-time data of the route optimization is lacking.
(B. G. Wilson & Vincent, 2008)	Global positioning system	Analyzing the delay of vehicles at the transfer station.	Limiting the analysis to 1 year of data may have concealed a few seasonal dissimilarities in the data.
(O'Connor, 2008)	Global positioning system	Communicates the precise activities of drivers	A real-time communication system is not addressed.
(Rovetta et al., 2009)	Global positioning system & Geographic information system	Spatial data and real-time data for tracking and optimizing the collection.	Sensor fusion techniques are not utilized for the classification of waste.
(Nielsen et al., 2010)	Global positioning system & RFID	Automated billing and route optimization.	RFID technology is only able to communicate only information to a limited range.
(Mundhe et al., 2014)	Global positioning system & Geographic information system	Integrating for assessing the waste management system.	Assessment is limited to the theoretical approach.
(Zeeshan et al., 2018)	Global positioning system & Geographic information system	Geographic information system & Global positioning system for selecting a feasible location	A tracking system needs to be implemented for making the system effective.

The authors of (Yang et al., 2008)developed a method for landfill site selection by analyzing anaerobic decomposition and gas emissions from landfills. In a metropolitan region of Jiangsu province, China, the system investigates the remotely sensed environmental characteristics around landfills and evaluates conformity of their location and leachate quality with applicable national laws. The system's strength is the establishment of a remote monitoring approach for identifying landfill sites that take into account man-made environmental concerns in order to alleviate potential health problems. Unfortunately, providing real-time information is difficult, and it can only provide a limited service to solid waste management.

Table 2.3 Remote Sensing in Solid Waste Management

Ref	Spatial technology	Function	Limitations
(Yang et al., 2008)	Remote sensing	Allotting landfill site which is far away from water bodies.	Implementation of RS & geographic information system increases the infrastructure cost.
(Adeofun et al., 2012)	Remote sensing	Selecting a waste disposal site.	In optimal routing, the profile of the road has not been considered.
(Karsauliya, 2013)	Remote sensing & Geographic information system	Evaluating the feasible site for disposal of waste far away from the river bodies.	Time-consuming and high cost for real-time implementation.
(Dutta & Goel, 2017a)	Remote sensing & Geographic information system	Analyzing the waste generation.	Simple Thiessen polygons to evaluate the impact of activities on a specific area with single remote sensing imagery.
(Vambol et al., 2019)	Remote sensing	Detecting unauthorized landfill sites.	Detection time is maximum.
(Richter et al., 2019)	Remote sensing & Geographic information system	Ranking the landfill site.	Thiessen polygons for obtaining the area of influence around polygons and the usage of a single RS image.

Table 2.3 presents solid waste management systems based on Remote Sensing technology. The use of Remote Sensing -based systems in solid waste management includes a selection of disposal sites (Jensen & Christensen, 1986), environmental features and impact monitoring for solid waste disposal sites (Yang et al., 2008), and environmental impact assessment. The analysis of the spatial technologies concludes that the implementation of these technologies consumes requires high-end infrastructure and is time-consuming. Unfortunately, it is incapable to deliver real-time information, which is primarily required in ICT for monitoring waste.

2.2 Real-time Technologies in Solid Waste Management

Real-time monitoring of garbage bins has become more feasible and accessible as sensing and communication technology has advanced (Hannan et al., 2015b). The ability of these technologies to provide information on bin status motivates the use of various sensors and wireless sensor networks (WSN) that employ a combination of short- and long-range communication technologies. On other hand, the advancement in Internet protocols enabled monitoring the devices through the internet (Weber et al., 2017). The Internet has transformed the world and provided global connectivity. In the same manner, the IoT paradigm is primarily responsible for facilitating the integration of various application and communication technologies, such as identification and tracking, sensor networks, wired and wireless actuators, improved communication protocols, and distributed intelligence for objects (Zanella et al., 2014). The integration of sensors, actuators, and communication protocol with the internet establishes a real-time monitoring system. The sensors and actuators embedded in the physical things can transmit real-time information through a communication protocol.

In the early stage of real-time monitoring, the WSN is implemented to monitor the bin status wirelessly (Lata & Singh, 2016; Lokhande & Pawar, 2016; Narendra Kumar et al., 2014), where researchers have integrated the webserver for visualizing the filling of bins (Suryawanshi et al., 2018). With this motivation, the convergence of Ultrasonic Sensors, RFID, and GSM technologies for solid waste management is established to implement an intelligent solid waste collection system (Cavdar et al., 2016b). An intelligent solid waste bin with three different sensing units is integrated to sense lid status, waste level, and weight and when the lid is opened, the accelerometer activates the three sensor systems (Al Mamun et al., 2015), (Hannan et al., 2016). A study has integrated an ultrasonic sensor, GSM, RFID system, an RFID tag and embedded it in two containers for real monitoring of truck and route optimization during collection (Cavdar et al., 2016a). In (Marques et al., 2019) proposed an architecture that uses Raspberry Pi hardware with AQMP and XMPP Communication protocols for providing a better quality of service to the user. The sensors are the primary unit for the implementation of real-time monitoring and the sensors help to monitor the physical environment. Table 2.4 presents the type of sensors that are implemented in solid waste management for detecting the level, waste sorting, and waste collection. A Green IoT-based waste management system is proposed to reduce waste and the emission of greenhouse gases Ultrasonic Sensor (HC SR04) and gas sensors (Misra et al., 2018). Raspberry Pi 3 and ultrasonic sensors-based system proposed for detecting the level and suggested to integrate RFID for better identification of the bins (Maksimovic, 2018).

Table 2.4 Sensors in Solid Waste Management

Ref	Sensors	Application	Function
(McLeod et al., 2013b)	Infrared sensor	Scheduling for collection	Enhancing the waste collection event.
(Maksimovic, 2018)	Ultrasonic sensor	Detection of bin level	Level sensing of waste in the bin.
(Chaudhari et al., 2019)	Ultrasonic sensor	Waste collection	Enabled threshold limit to the bin for overcoming the overflow of waste from the bins.
(Durrani et al., 2019)	Infrared sensor	Bin level	level measurement of waste in the bin.
(Vasagade et al., 2020)	Infrared sensor	Waste collection	Monitoring the level of waste.

(Hannan et al., 2012)	Camera	Waste collection	Improving the efficiency of the collection system.
(Szoke-sieswerda & Szoke-sieswerda, 2014)	Camera	Outdoor condition of bin	Monitoring the outdoor condition of the bins.
(Yu, 2020)	Camera	Bin identification	Identifying the bins during classification.
(Rad et al., 2017)	Camera	Classification of waste	A deep learning framework is implemented on the image that was acquired through the camera.
(Chinnathurai et al., 2016)	Camera	Bin sorting	Mounted camera in the robot for sorting the waste in the bin.
(Yun et al., 2019)	Camera	Monitoring dumping	Real-time monitoring activities in the dumping yard.

Table 2.5 presents the implementation of IoT for solid waste management, where the IoT is used for monitoring the different activities like monitoring the level and stinky gases, waste discharging, waste collection, reduce food waste. From table 2.5, it is concluded that the major focus is done on monitoring the filling level of the bins. To quantify the level of the waste, an ultrasonic sensor can be embedded in every bin. In a few studies, the proximity sensor is embedded for sensing the nearby object and enabling the lid to open for disposal of the waste. Force resistive sensor & load cell sensor are embedded for quantifying the quantity of the waste in the bin. Fire sensor is for sensing the fire or smoke in the bin, gas sensor is for sensing the possible evolution of pungent gas from the waste, odor sensor for sensing the smell from the waste in the bin, and moisture sensor is to monitor the wetness on the waste. With the evolution of cloud computing technology, the bins can be monitored through IoT. Cloud is one of the promising computing technologies where the data is analyzed, computed, and stored. The different platforms of cloud are implemented in literature including Ubidots, Google cloud server, Thingspeak server, amazon web server, and local server.

Table 2.5 IoT in Solid Waste Management

Ref	Objective	Waste	Sensors	Software
(Chaudhari et al., 2019)	Monitoring level	Solid waste	Ultrasonic sensor, weight sensor	Local server
(Hong et al., 2014)	Reduce food waste	Food	Load cell	Mobile API,
(Popa et al., 2017)	Waste discharging and collection	All	Ultrasonic, proximity & fire	Amazon webserver (AWS)
(Indexed et al., 2018)	Monitoring level	Solid waste	Ultraviolet (UV)	Web portal
(Jinila et al., 2019)	Waste collection & monitoring level	Household waste	Ultrasonic sensor	Cloud server
(Memon, Karim Shaikh, et al., 2019)	Monitoring level	Solid waste	Ultrasonic sensor	Mobile API
(Soh et al., 2019)	Monitoring the level & alerting	Solid waste	Ultrasonic sensor	Ubidots IoT Cloud
(Shirke et al., 2019)	Monitoring level & moisture	Solid waste	Ultrasonic sensor, moisture sensor	Local server
(Hussain et al., 2020)	Monitoring level & weight	Solid waste	Ultrasonic sensor, weight sensor, an odor sensor	Google Cloud (GCP)

Figure 2.1 shows the IoT architecture of solid waste management. In this architecture, ‘n’ number of the bins in the perception layer are considered with communication capability to transmit the filling level of the bin. The nodes are deployed in the bins which enables communication to the cloud server with GSM/ Node MCU modem. In IoT, the selection of the controller and wireless communication is very important as the sensor node are energy-constrained devices. Nodes positioned in the outdoor ecosystem require an additional electrical power grid. GSM/GPRS communication consumes power consumption and a prepaid amount needs to be recharged for transmitting the data (Satria & Hidayat, 2019; Zavare et al., 2017). The data transmission range of ZigBee is limited to

short-range and however, the transmission range can be increased by installing Zigbee repeaters. Installation of Zigbee repeaters is having a higher possibility of connectivity failure. Wireless communication technologies like GSM, Zigbee, cdma2000 ev-do, and RFID are being integrated for establishing the interconnection between bins and servers. Node MCU and RKI-1451 have been implemented for communicating sensory data over the internet.

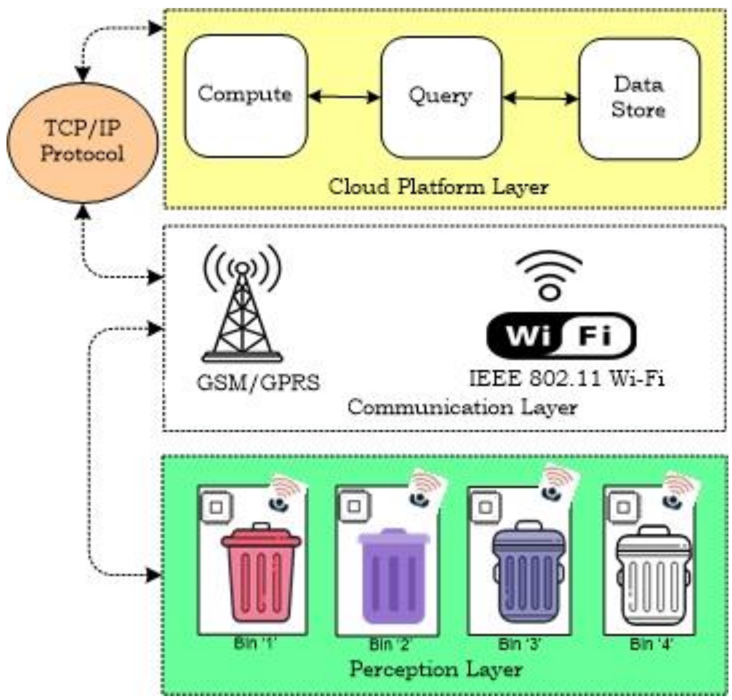

Figure 2.1 IoT Architecture for Solid Waste Management System (Marques et al., 2019)

The limitations of integrating the GSM/GPRS, Zigbee, and Wi-Fi-based Node MCU for IoT-based solid waste management in terms of transmission range, high energy consumption, and additional electric grid infrastructure. However, the evolution of LoRa protocol has widened the opportunities for implementing IoT architecture to waste management, as this technology is capable of transmitting wireless data in the absence of remote cell technology with low power consumption (Augustin et al., 2016; Saari et al., 2018). A study has implemented the low power consumption LoRa nodes for the optimization of waste collection routes (Lozano, Caridad, De Paz, González, et al., 2018) (Lozano, Caridad, De Paz, Villarrubia Gonzalez, et al., 2018). An architecture is implemented to measure the filling level of the dustbin by using low powered sensor and ATMega 328 microcontroller (Cerchecci et al., 2018b) (Cerchecci et al., 2018a).

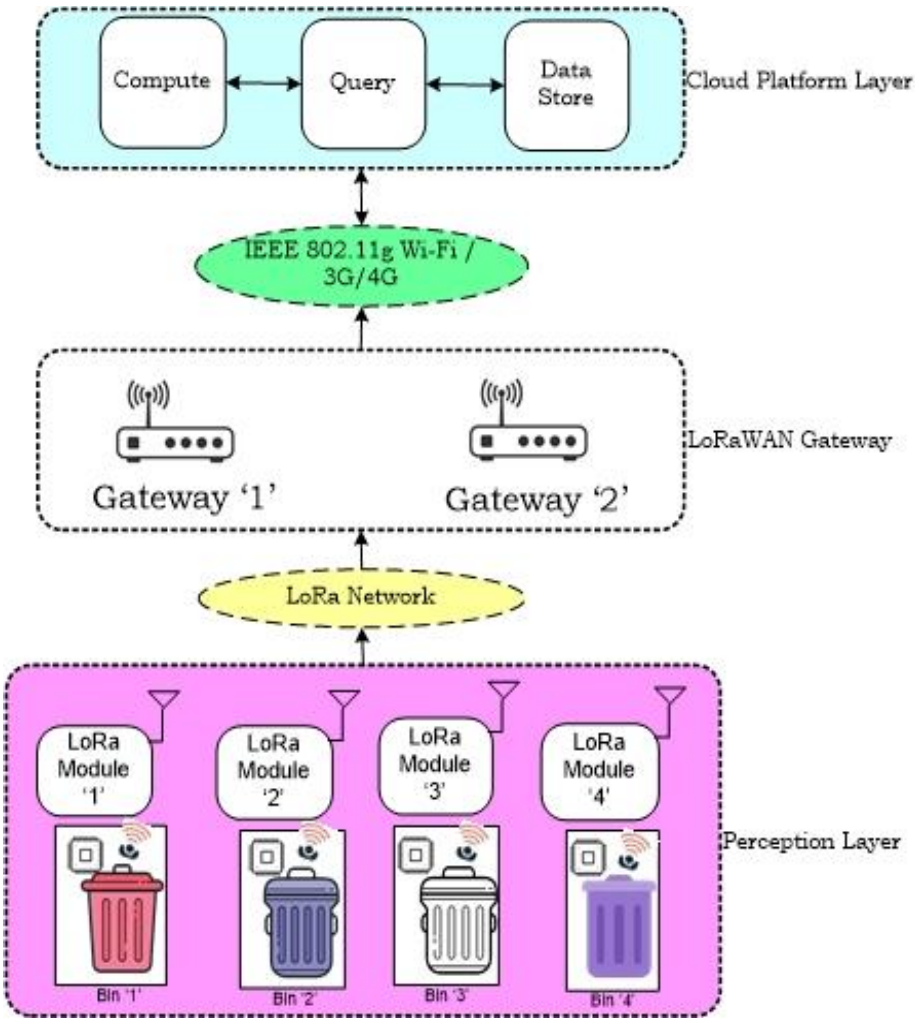

Figure 2.2 LoRa & IoT Architecture for Solid Waste Management (Cerchecci et al., 2018a)

A recent study integrated the Raspberry Pi 3 Model B+ controller unit and LoRa communication protocol to examine the filling level in the bin (Anh Khoa et al., 2020). The LoRa enabled architecture for solid waste management is shown in figure 2.2. LoRa is embedded in the sensor nodes to transmit the sensory data to the gateway. The gateway uses the internet connection to log the sensory data into the cloud server. The gateway is the integration of the LoRa network and IEEE 802.11 Wi-Fi/ 3G/ 4G which is capable of receiving the data from the nodes and communicating it to the cloud server for computing and storage. LoRa is an optimal wireless communication technology for the implementation of solid waste management.

2.3 Blockchain

Blockchain technology integration with IoT enables the creation of a trustworthy business market, service between the device & cryptography-based authentication to automated devices in IoT (Konstantinos Christidis & Devetsikiotis, 2016). A framework is implemented for baby monitoring with blockchain technology and IoT through Raspberry pi and camera module (Ouaddah et al., 2016). BlendCAC model is implemented with smart contract and blockchain technology for IoT access control in a decentralized manner (R. Xu et al., 2018). A smart city architecture based on software-defined networking and blockchain technology is proposed to address the issues of latency, bandwidth bottlenecks, flexibility, confidentiality, and privacy (P. K. Sharma & Park, 2018a). The scalability problem of IoT is overcome with an architecture based on the blockchain network and also it can improve the security of IoT due to the presence of a proof-of-concept prototype (Novo, 2018). An efficient distributed storage system based on smart contracts is implemented and OSD in the system operates as transaction protocol (Q. Xu et al., 2018).

An ICT e-agriculture system is implemented, where the blockchain infrastructure is integrated with ICT for exchanging information at the national level as well as a regional level (Y.-P. Lin et al., 2017). Hybrid Blockchain and IoT are combinedly used for monitoring the structure of an underground building, where the centralized and decentralized characteristics have been divided into core and edge networks (Jo et al., 2018). Blockchain technology is used to authorize the activities of resource monitoring and trading for managing the resources in an intelligent and decentralized manner (Alcarria et al., 2018). The double chain architecture using public blockchain in agriculture supply is proposed for assuring not only security and privacy but also provides credibility for public service platforms (Leng et al., 2018). The integration of blockchain with artificial intelligence for water management, and supply, where information about water distribution is stored in blockchain, and artificial intelligence is used to predict water distribution patterns (Y.-P. Lin et al., 2018), (Dogo et al., 2019). Lightning networks and smart contracts were used to create a method for securing electric vehicles and charging piles (X. Huang et al., 2018). A proof of concept is proposed with blockchain technology in solid waste management, where the payment will be executed based on the amount of the waste (Lamichhane, 2017). A waste tracking system is proposed with blockchain technology by involving the different entities to monitor data from the platform (P. K. Gopalakrishnan et al., 2020). A solid waste management model is proposed for enhancing the mechanism of waste management through blockchain technology (P. K. Gopalakrishnan et al., 2021).

An architecture is proposed for the supply chain to validate and track the product with a private distributed ledger and public blockchain (H. Wu et al., 2017). Blockchain technology is used to eradicate illegal drugs, maintain quality drugs and manage the electronic medical record of patients(Hoy, 2017). The information-sharing of the different government organizations like revenue, identity verification, health information, judicial decisions, ownership of transport, and policy framing using blockchain technology (Ølnes et al., 2017). A prototype is implemented with blockchain technology for evaluating distributed personal health records and it is tested by considering datasets of 40 thousand patients from two different hospitals (Roehrs et al., 2019). A blockchain-based traceability prototype is deployed to eliminate data manipulation during traceability (Q. Lin et al., 2019). An open manufacturing framework is carried out for sharing the information and knowledge among the different entities of the manufacturing with blockchain and edge computing (Z. Li et al., 2017). A novel ethereum assisted framework is proposed for data preservation in medical and this framework is reliable for storing the personal medical data and maintains the originality of the data (H. Li et al., 2018). Gcoin a blockchain platform is recommended for knowing the data flow of drugs and also creating a transparent data transaction of drugs for overcoming counterfeit, drugs (Tseng et al., 2018). The private blockchain is been used for providing a decentralized platform for consumers and prosumers of 100 householders for trading the local energy generation (Mengelkamp, Notheisen, et al., 2018). Smart contracts and energy blockchain are used for securing the charge of electric vehicles in a smart city and the energy consumption and utilization of the electric grid are monitored securely (Su et al., 2018). An open manufacturing framework for sharing the information and knowledge among the different entities involved in manufacturing by bringing different technologies in blockchain and edge computing (Zhang et al., 2020). Efficient management of microgrid energy market a blockchain-based microgrid energy framework is proposed (Mengelkamp, Gärttner, et al., 2018). Blockchain and the Continuous Double Auction (CDA) mechanisms are used in a study of electricity transactions for assisting customers and retailers to match transactions in the market due to price fluctuation (Wang et al., 2017). A demand response of energy in a smart grid is examined using multiple residential energy data sets, where the evaluation of demand response in the smart grid is processed with consensus-based validation (Pop et al., 2018).

2.4 Conclusion from the Review of Literature

In the review of literature, the existing techniques that are applied in solid waste management are carried out. The following are the research gaps that are identified from the review of literature:

- Real-time hardware implementation with the blockchain in solid waste management needs to be explored.
- Implementation of LoRa with IoT network for efficient waste monitoring and management needs to be studied.
- Sustainable sanitation and circular economy by implementing blockchain in solid waste management are not yet explored.

The table 2.6 illustrates the mapping of research gaps with research objectives. In this, research objective is linked to the respective research gap in detail.

Table 2.6. Mapping of Research objectives with research gaps

S.No	Research Objective	Research Gap
1	To design sensor node for the bins with communication capability	Real-time hardware implementation with the blockchain in solid waste management needs to be explored.
2	To establish LoRa network between the bins	Implementation of LoRa with IoT network for efficient waste monitoring and management needs to be studied.
3	Development of waste management server	Implementation of LoRa with IoT network for efficient waste monitoring and management needs to be studied.
4	Integration of lightweight blockchain server with waste management server	Sustainable sanitation and circular economy by implementing blockchain in solid waste management are not yet explored

2.5 Chapter Summary

The chapter discusses the existing literature that focused on the different techniques implemented in solid waste management. The chapter includes the conclusion from the existing literature and a research gap that supports the formulation of objectives and methodology. It is concluded that blockchain technology can be implemented in solid waste management along with hardware for enhancing the mechanism of solid waste management.

A review article is published about the distinct technology role in the solid waste management for wireless monitoring and the **publication** is: Shaik Vaseem Akram, Rajesh Singh, Anita Gehlot, Mamoon Rashid, Ahmed Saeed AlGhamdi, Sultan S. Alshamrani, and Deepak Prashar. "Role of Wireless Aided Technologies in the Solid Waste Management: A Comprehensive Review." is published in Sustainability, MDPI, (SCI).

Chapter 3
System Description

In this chapter, the system architecture and hardware development are discussed. The complete working of the system architecture along with the block diagram is discussed. The description of components selected for the sensor node and gateway is also discussed along with the Proteus Simulation model. The significance of hardware customization of sensor nodes and gateway are presented along with circuit diagram and PCB design.

3.1 System Architecture

Waste management is a significant administrative unit that monitors and supervises the activities of the waste from the collection to the disposal. The system architecture proposed in the present research for the waste management system includes the waste-to-money model based on blockchain and the LoRa network. The waste-to-money model is to be implemented in between the waste generator (individual) and recycling unit (organization). The waste generated by an individual in a community area is connected to the recycling unit through a cloud server. An individual can gain value in terms of money from the recycling unit on the basis of the amount of waste is generated. The blockchain supports the recycling unit to validate and authenticate the sensory data received from the waste generator to execute transactions.

The system architecture (figure 3.1) describes the working of the system implemented for the waste management system. The key units of the system architecture are sensor node, gateway, intelligent waste management server, and blockchain. The real-time data of the bins are processed for logging on to the cloud server and also for implementing the blockchain. The sensor node communicates the sensory data of the bins to the gateway. LoRa communication transmits only the radio frequency (RF) packets, and to record, the data on the cloud server, IP packets are required. The gateway connects two networks of distinct wireless communication protocols. The gateway is embedded with both wireless communication protocols namely: Wi-Fi module and LoRa.

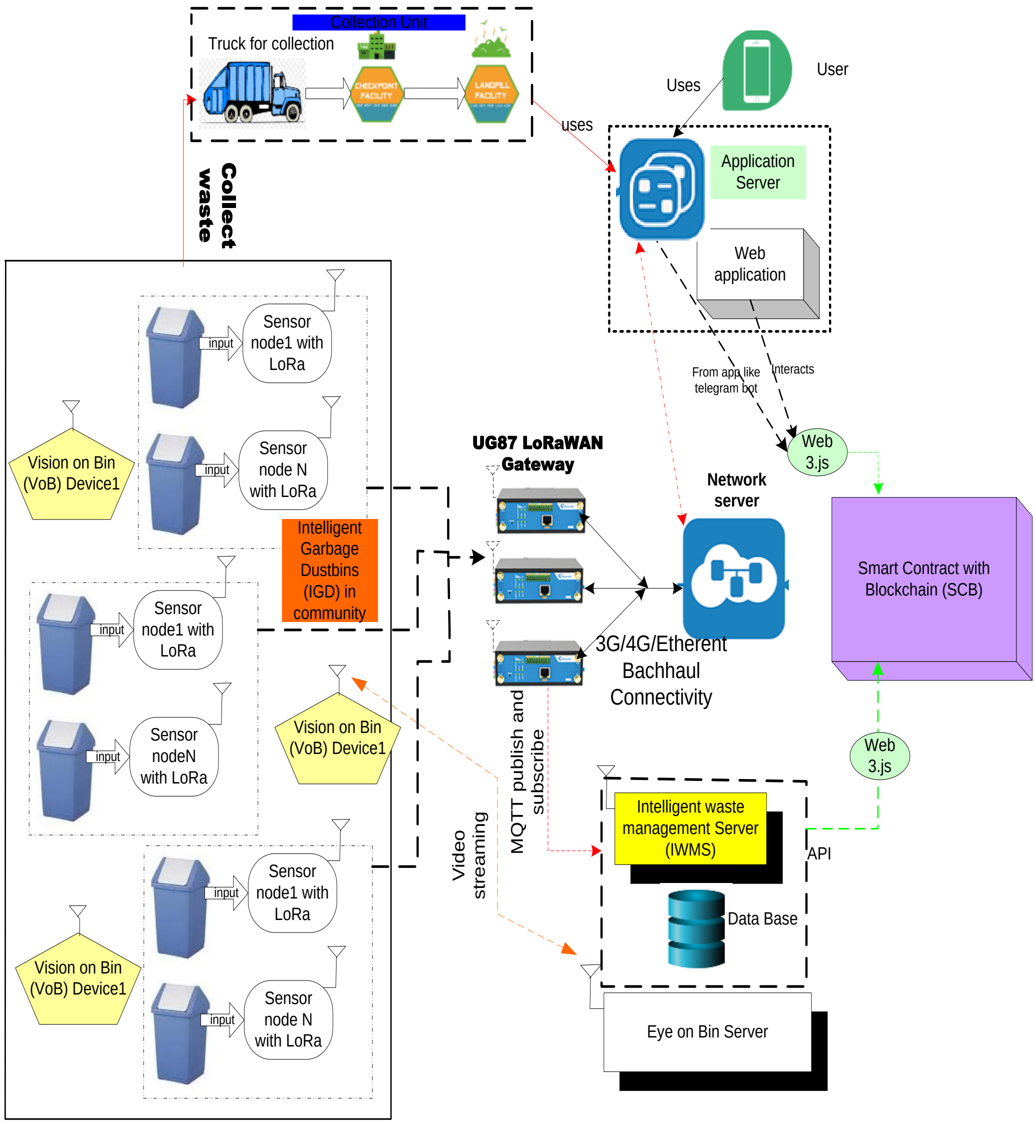

Figure 3.1 LoRa and Blockchain-based Proposed Architecture for Solid Waste Management

The gateway is positioned at the place where it can access the internet connectivity. The gateway receives the data from the sensor node through LoRa and communicates it over the IP to the cloud server with a Wi-Fi module. The cloud server is integrated with blockchain through a Web API. The blockchain validates the sensory data like the waste level in the bins and based upon the quantity of the data, the blockchain generates a specific amount and credits into the individual account.

3.2 Sensor Node

The sensor node is the unit of the architecture which collects and communicates the sensory data of the bins to the cloud server. A sensor node is embedded with four components namely controller unit, communication module, sensors, and power supply unit as shown in figure 3.2. The Controller unit is interfaced with the sensory unit, communication module, and power supply unit (figure 3.2).

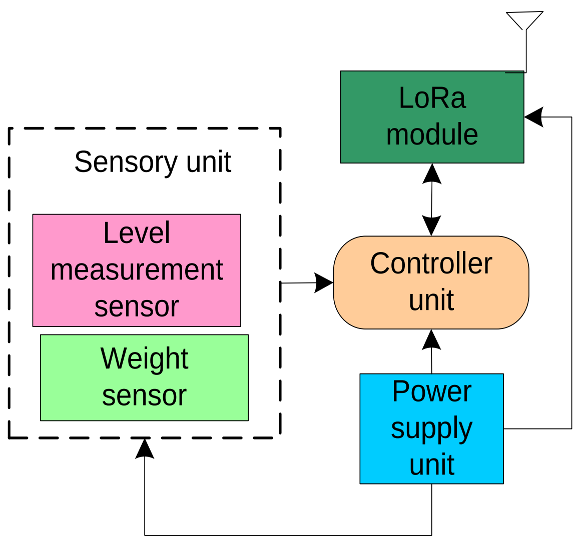

Figure 3.2 Block Diagram of Sensor Node

ATMega 328P microcontroller (Corporation, 2015) unit is considered for the sensor node as per the complexity of the processing requirement. It is an 8-bit AVR microcontroller based on RISC architecture, with low power consumption. RISC architecture enables ATmega 328P to execute 1 MIPS per 1MHz. The programming of the ATmega 328P controller is convenient and flexible, as its programming is done with the Arduino IDE in the C++ language. The technical specifications of the ATmega 328P microcontroller are presented in table 3.1.

Table 3.1 Specifications of ATMega328P Microcontroller

Parameter	Specification
Processor	8-bit
Architecture	RISC
Flash memory size	32-kilo bytes (KB)
CPU speed	20 MIPS
Programming	In-system programming
Serial interface	Master/slave SPI
PWM channels	6
Pin	6 analog pins 14 digital pins
Voltage	2.7 V to 5.5 V
Current,	Power-down state: 1 uA at 3V; Active state: 1.5 mA at 3 V–4 MHz
Clock speed	16 MHz

Table 3.2 Specifications of SX 1278 Module

Parameter	Specification
Frequency	433 MHz
Network topology	Point-to-Multipoint, Point-to-Point, Mesh, and Peer-to-Peer
Modulation	FSK/GFSK/MSK/LoRa
Data rate	<300 kbps
Sensitivity	-136 dBm
Output power	+20 dB
Voltage	1.8 V to 3.6 V
Current	Tx: 120 mA, Rx: 10.8 mA
RSSI	127 dB
Link budget	168 dB

The communication module LoRa is connected to transmit the sensory data to the gateway. SX1278 LoRa module (Semtech Corporation, 2016) is based on LoRa modulation and operates in the frequency band of 433 MHz (ISM band). The technical specifications of the SX 1278 LoRa module are presented in table 3.2. A sensor unit is developed to sense the different parameters of the bins. The level and weight of the waste in the bins are measured with weight sensor and level measurement sensor respectively. The level of waste in the bin is detected by a level sensor in the sensor node, which measures the level of the waste in the bins. The HC SR 04 sensor (Voltage et al., n.d.)is used to measure the distance between objects. After the generation of ultrasonic waves by the sensor, the head of the sensor detects the reflected target waves. The duration between emission and reception of ultrasonic waves is considered for measuring the distance of the object (figure 3.3). This sensor has a four-pin module, namely: echo, trigger, Vcc, and ground and it can measure the distance within the range of 2cm to 400 cm. The technical specifications of the HCSR04 are shown in table 3.3.

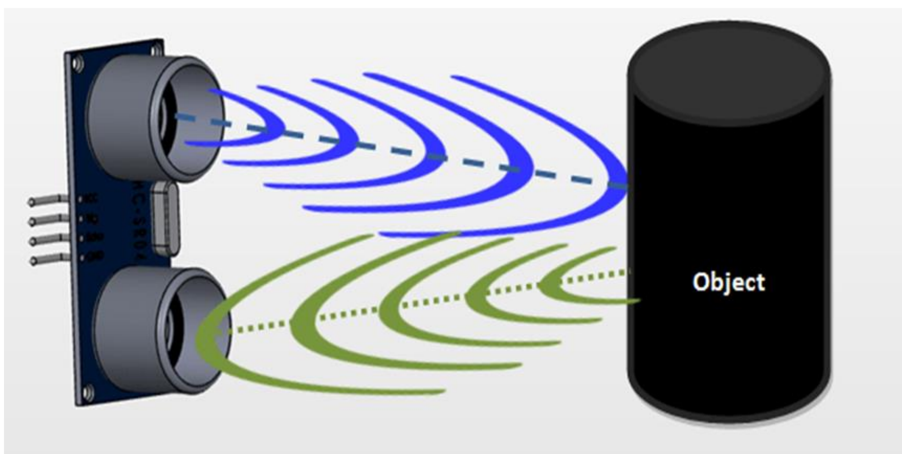

Figure 3.3 HC SR 04 Sensor

The weight sensor in the sensor node measures the weight of the waste, filled in the bins. The weight sensor connects the force placed on it into an electrical signal. Load Cell (Description, 2015)acts as a weight sensor and comprises four strain gauges, and it is based on Wheatstone Bridge Circuit. The specifications of the load cell sensor are presented in table 3.4. The power supply unit is to provide power to the interfaced components with the node. The sensor node comprises three different power supply pins namely: +5V, +12V, and +3.3V for powering the components with distinct voltage. In the sensor node, the operating voltage of the ATMega 328P microcontroller is 2.7V- 5.5V, the LoRa module is 1.8-3.6V, and the Level sensor is 5V.

Table 3.3 Specifications of HCSR04 Sensor

Parameter	Specification
Pins	Four (Vcc, GND, trigger, echo)
Measuring distance	2 cm to 450 cm
Operating voltage	+5V
Operating current	< 15mA
Accuracy	3mm

Table 3.4 Specifications of Load Cell Sensor

Parameter	Specification
Circuit	Wheatstone Bridge
Type	Strain gauge
Operation	Tension-Compression
Range	Up to ±110Kg
Accuracy	3mm

3.2.1 Proteus Simulation Model of Sensor Node

Proteus is a Virtual System Modeling and Circuit Simulation program. It integrates the Simulation Program with Integrated Circuit Emphasis (SPICE) circuit simulation, components, and microprocessor models to enable co-simulation of microcontroller designs. Proteus also simulates the software running on a microcontroller with any analog or digital devices that are connected to it. The proteus model of the sensor node is presented in this section with a detailed explanation. The Sensor node comprises of level measurement sensor, load cell sensor, and LoRa module. The working flow diagram of the sensor node is illustrated in figure 3.4. The main purpose of the sensor node is to collect sensory data and communicate it to the gateway. The function of the sensor node starts by initializing the serial peripheral interface (SPI). After that, the status of the sensor node is checked. In case the sensor node is in working mode, then the sensor acquired the data of the bins. As the sensor obtains the data of the bins then the LoRa module is set for communicating the data to the receiver in the microcontroller of the sensor node.

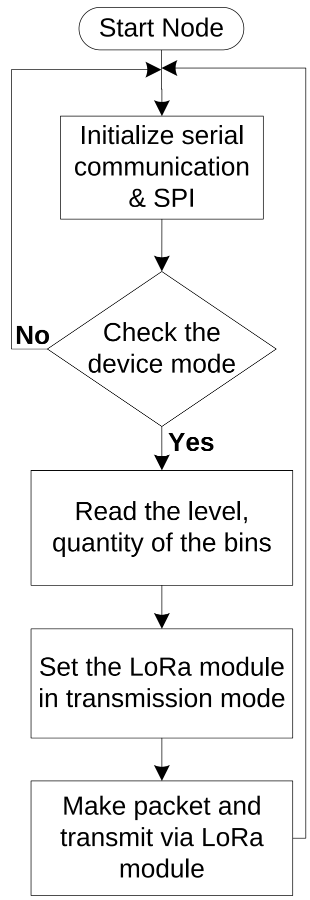

Figure 3.4 Working Flow of Sensor Node

The sensor data of the bins are converted into a packet and transmitted via LoRa communication. Proteus is generally utilized for drawing and designing electronic circuits before designing a PCB board. To evaluate the circuit design, a proteus simulation is performed. To check the workflow of the sensor node, a proteus simulation is carried out. Figure 3.5 presents the proteus model of the sensor node. Here Arduino Uno is considered as it is integrated with the same ATmega 328P microcontroller that is utilized for the sensor node**.** Pin 6 of the Arduino UNO is used for the ultrasonic sensor's echo pin; pin 7 is used for the sensor's trigger pin. In serial communication, the Arduino Uno's receiver (RxD) and transmitter (TxD) are connected. The simulation is carried out for the sensor node through serial communication and the sensor node visualizes the sensor data on the LCD connected to the Arduino Uno.

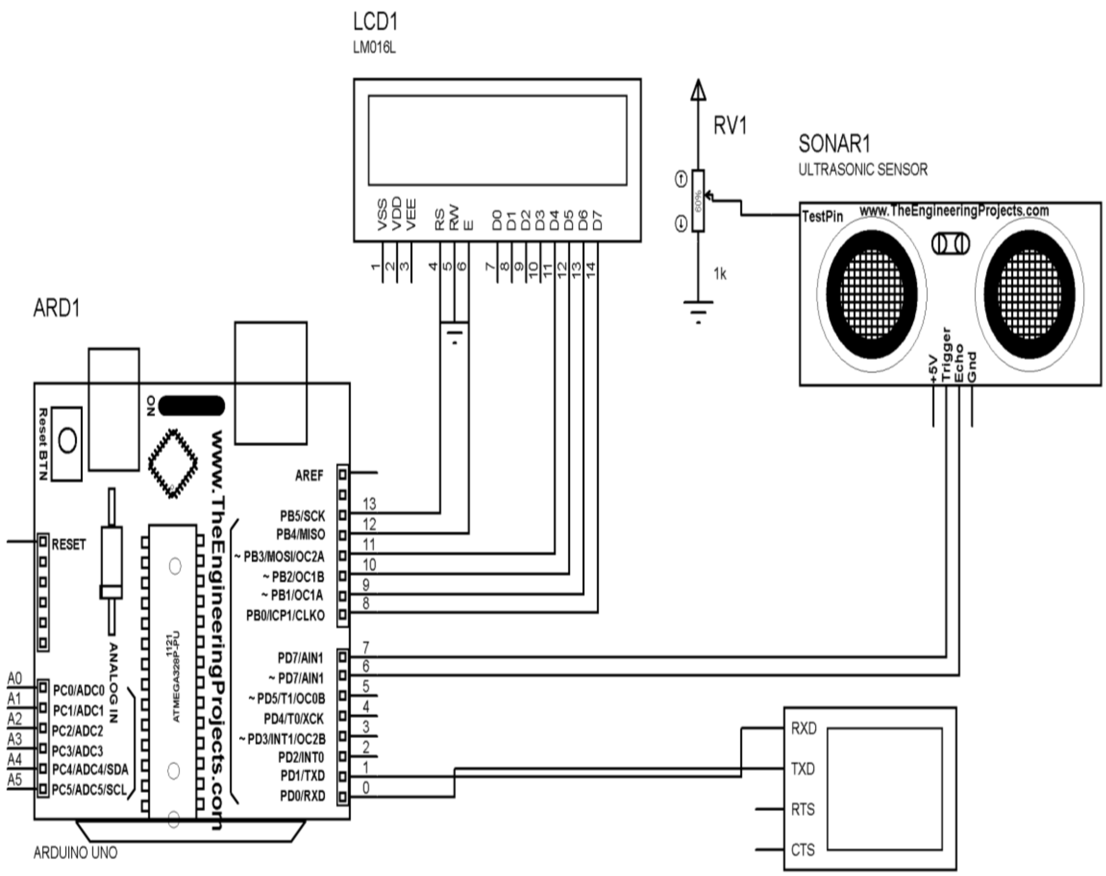

Figure 3.5 Proteus Simulation Model of Sensor Node

3.3 Gateway

The gateway acts as a bridge to connect two distinct wireless communication protocols. Figure 3.6 presents the block diagram of the gateway. The Controller unit, Wi-Fi module, LoRa module, and power supply unit are the four components of the gateway. The Controller unit is interfaced with a sensor unit, two communication modules, and a power supply unit. ATMega328P microcontroller is considered for gateway. The importance of integrating the microcontroller unit in the gateway and the technical specifications are already discussed in section 3.2 and table 3.1. LoRa module and Wi-Fi module are interfaced to the gateway for connecting the sensor node to the cloud server. SX1278 LoRa module (433MHz) interfaced to the gateway transmits the sensor data from the sensor node through RF packets.

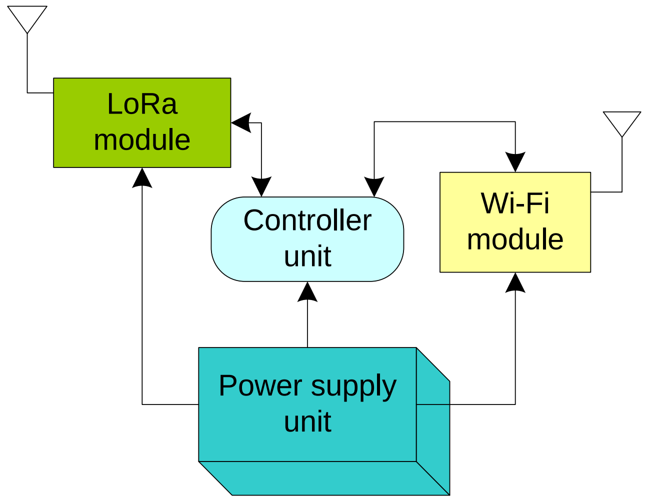

Figure 3.6 Block Diagram of Gateway

Table 3.5 Specifications of ESP8266 Wi-Fi Module

Parameter	Feature
Processor	Tensilica L106 32-bit processor
IEEE standard	802.11 b/g/n
Frequency	2.4 GHz
Data rate	72 Mbps
Network Protocols	Ipv4, TCP/UDP, HTTP
Tx power	17 dBm (802.11 g), 20 dBm (802.11 b), & 14 dBm (802.11n)
Sensitivity	-91 dBm (802.11 b), -75dBm (802.11 g) & -71 dBm (802.11n
Voltage	2.5 V to 3.6 V
Current	Average: 80mA

The sensor data is required to communicate in IP packets over a cloud server and the Wi-Fi module (IEEE 802.11standard) interfaced to gateway transmits the sensory data in IP packets. ESP8266 Wi-Fi (IEEE 802.11) (*ESP8266 Wi-Fi MCU I Espressif Systems*, n.d.)

is the Wi-Fi module interfaced to the gateway to transmit the packets through the internet. The technical specifications of the ESP 8266 Wi-Fi module are presented in table 3.5. The power supply unit provides power to all units including the LoRa module, Wi-Fi module, and controller unit.

3.3.1 Proteus Simulation Model of Gateway

The gateway consists of a LoRa module and ESP 8266 Wi-Fi is to bridge the sensor node and cloud server. The flow diagram of the gateway is shown in figure 3.7. The SPI is initialized for checking whether the LoRa module is functioning or not.

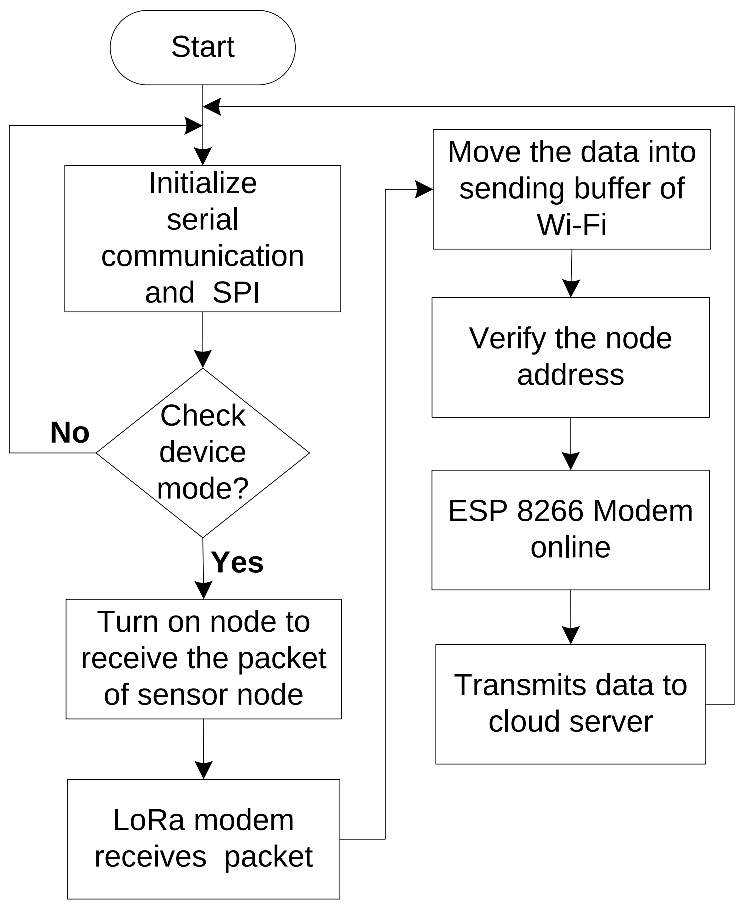

Figure 3.7 Working Flow of Gateway

When the LoRa module is functioning, then the gateway power on to verify whether the LoRa module receives the sensory data from the sensor node. The received data is exchanged and stored in the sending buffer of the Wi-Fi modem. The status of Wi-Fi (Online/offline) is validated after verifying the node addresses. The buffer data transmits to the cloud server when the status of Wi-Fi shift to Online. To check the workflow of the gateway a proteus simulation is carried out.

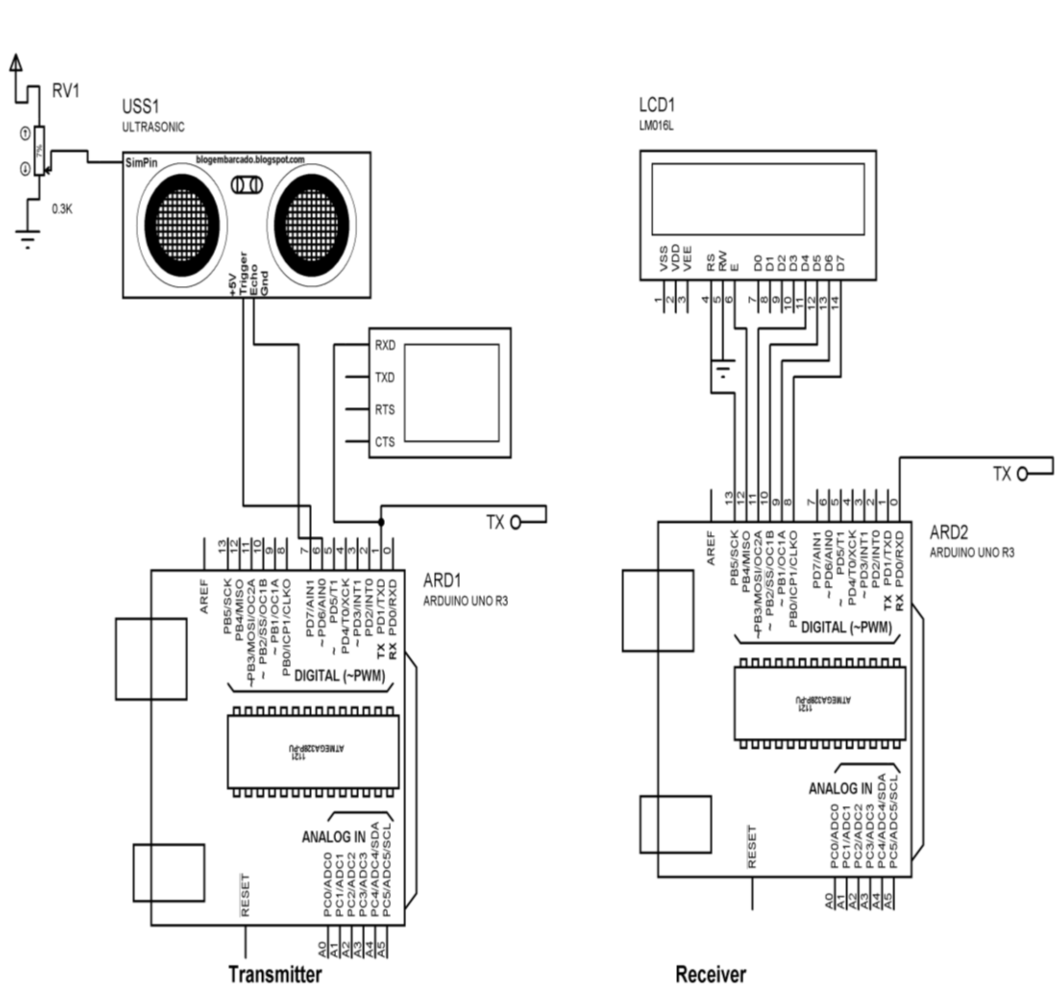

Figure 3.8 Proteus Simulation Model of Gateway

The Proteus simulation model of the gateway is presented in figure 3.8. The transmitter in the proteus simulation represents the sensor node and the receiver represents the gateway. Arduino Uno is considered in the proteus simulation, as it is integrating with the ATMega 328P microcontroller. The serial communication is established between the transmitter and receiver by connecting the TxD pin of the transmitter to the RxD pin of the receiver. RxD pin of the transmitter connected to the pin of TxD pin of the receiver. The simulation is carried out for the gateway, the transmitter (sensor node) can transmit the sensor data through serial communication to the receiver (gateway). The sensor node is visualized on the LCD of the gateway.

3.4 Hardware Customization

The customization supports to design and develop a system for a specific application. The controller board for IoT applications available in the market is general-purpose boards with limited power supply pins and constrained size. Size is one of the prominent design parameters for any system which helps to deploy the system in a specific location. Size can be reduced by selecting only the required number of analog and digital pins. The use of a large number of jumper wires to interface components is another challenge with boards. Even a minor fault in the connecting wire can significantly affect the system's performance. The customization of hardware allows selecting only required components for implementing the system. Depending upon the input/output components, the number of analog pins and digital pins can be selected on the board, which can reduce the complexity of size and space.

The power consumption is a crucial parameter for designing the nodes, as they are implemented in the outdoor environment where the electrical grid network may not be available, it may raise the infrastructure cost of deploying an independent electric grid network. In addition to powering the sensor node, a power jack is also embedded on the board for getting power supply through the battery or from any external source. The +5 V and +3.3 V voltage converters are integrated with the sensor node and gateway to provide the required voltage. The selection of a controller is another design challenge and selecting an appropriate controller enables the design of an energy efficiency node. Following the selection of appropriated components for the design of the node, the next stage entails the integration of these components into a single board for realizing the reliable, compatible, and flexible node.

3.4.1 Design of Customized Board for Sensor Node

The components that are chosen for the sensor node are presented in this section along with the block diagram, circuit diagram, and PCB layout. Figure 3.9 illustrates the components for the sensor node, where the selected components are interfaced with the controller unit. In addition, with the communication module and sensor unit, the sensor node is interfaced with the In-Circuit Serial Programming (ICSP) and Future Technology Devices International Limited (FTDI) programming pins. These programming pins in the sensor nodes enable to upload of the program. ICSP has used form programming with a bootloader in MCU and the FTDI port is connected for uploading a program written in Arduino IDE. As discussed early in section 3.2, the different power supply pins for supporting the required voltage are also integrated on the board of the sensor node.

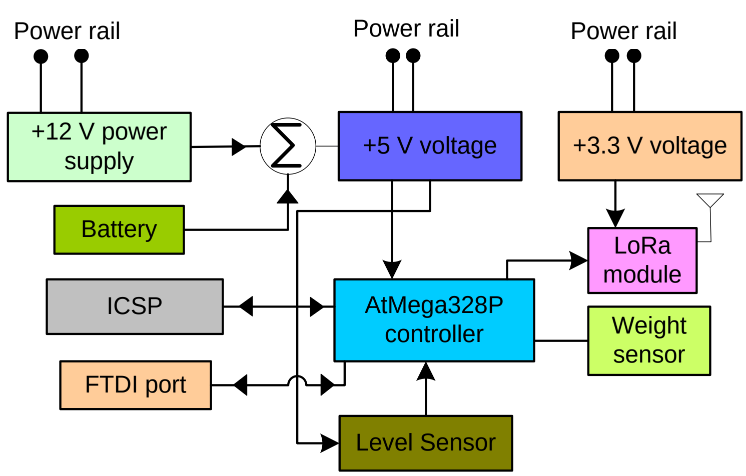

Figure 3.9 Components of Customized Sensor Node

All the selected components are integrated on circuit design as shown in figure 3.10 and it is as follows:

- The MOSI, MISO, SCK, GND, V_{cc} and RESET pins of the LoRa modem are connected with 15,16,17 GND, +5V, and RESET pins of the ATmega328 microcontroller respectively.
- Onboard +12V to +5V converter is connected to V_{cc} and GND pins of the ATmega328 microcontroller respectively.

- V_{cc}, trigger, echo, GND of the Ultrasonic sensor are connected to +5V, pin 11, pin 10, and GND pins of the customized board respectively.
- The FTDI port represents programmer pins, where this port enables the board to program the Atmega 328P microcontroller.

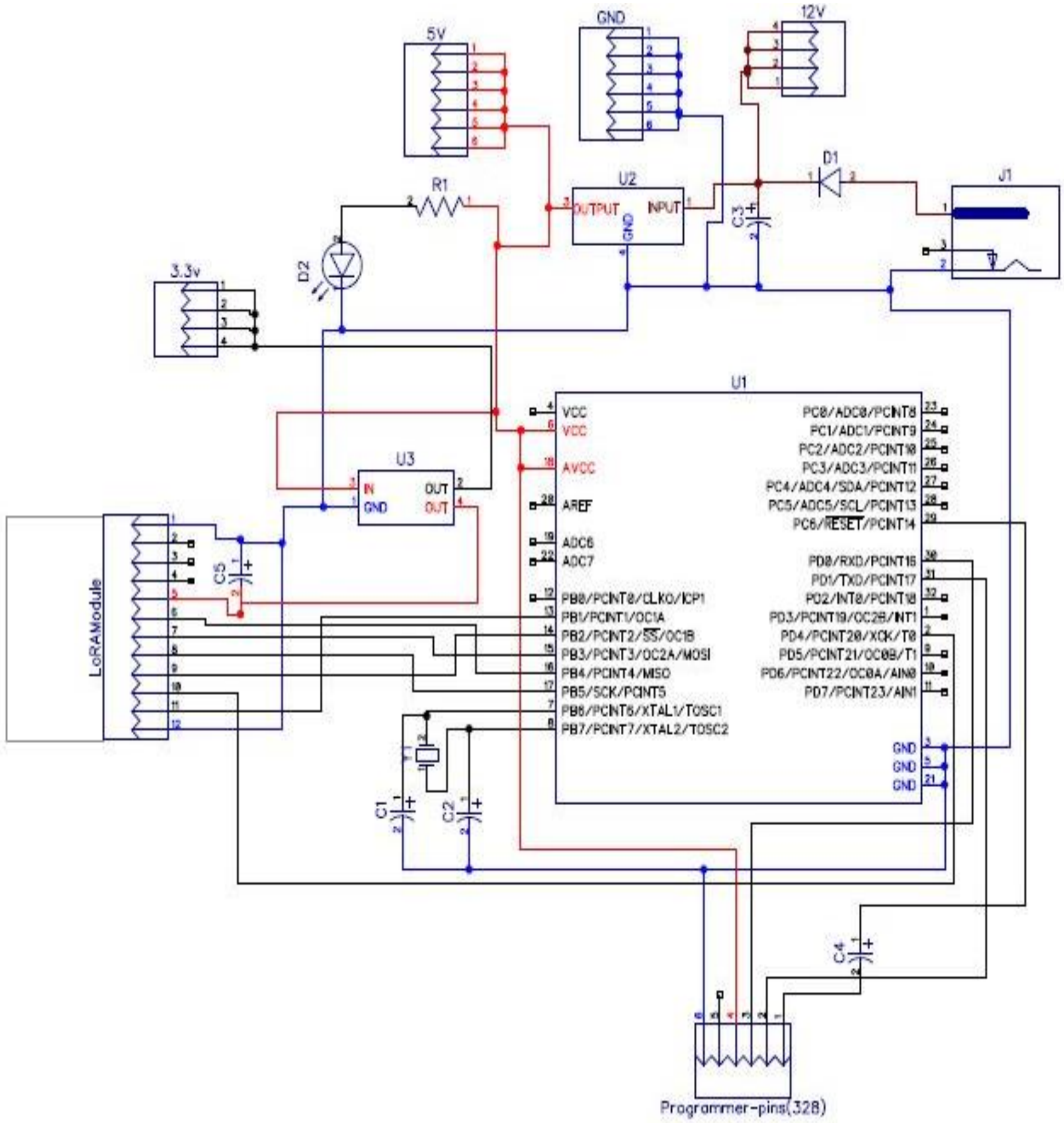

Figure 3.10 Circuit Diagram of Sensor Node

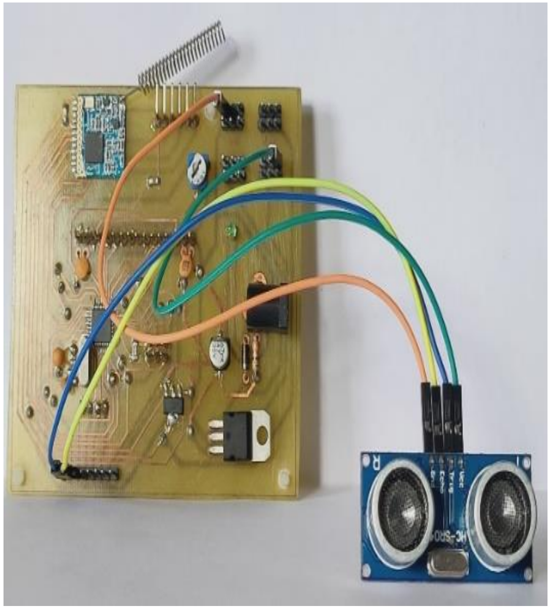 

Figure 3.11 Prototype of Sensor Node

Table 3.6 Features of Customized Sensor Node

Parameter	**Specifications**
Microcontroller	ATMega328P
Communication module	SX1278 LoRa module (433 MHz)
GND	6 Pins
Voltage converter	+3.3V and +5V
Power trails	+12V, +5V and +3.3V [6 power trails of each voltage]
Power jack	+12V External power supply
Programming pins	FTDI and ICSP

After designing the circuit of the sensor node, the prototype of the sensor node is developed as shown in figure 3.11. LoRa module and ATmega 328P microcontroller are interfaced on the sensor node. The sensor node is packed with protective material for enhancing the protection of the sensor node in the outdoor environment. The features of the customized sensor node are presented in table 3.6.

3.4.2 Design of Customized Board for Gateway

The components that are chosen for the gateway are presented along with the block diagram, circuit diagram, and PCB layout. Figure 3.12 illustrates the components of the gateway. As discussed in section 3.3, SX 1278 LoRa module is selected to enable the gateway to initiate communication with LoRa based sensor node. ESP 8266 Wi-Fi module is used to transmit the sensor data to the cloud through the internet. Similar FTDI and ICSP programming pins are integrated on the board of the gateway for programming purposes.

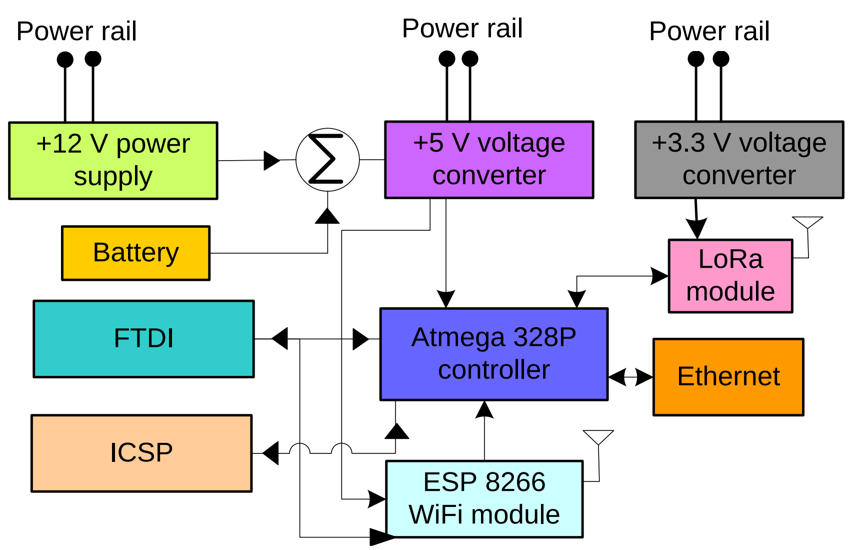

Figure 3.12 Components of Customized Gateway

All the components are integrated and designed a circuit for gateway (Figure 3.13). The connections of the gateway are as follows

- The MOSI, MISO, SCK, GND, Vcc and RESET pins of the LoRA modem are connected with 15,16,17 GND, +5V, and RESET pins of customized ATmega328 controller respectively.
- D6, D7 pins of the ESP8266 Wi-Fi module connect to the PIN 11 and PIN 10 of the ATmega 328P controller respectively.
- Two FTDI ports are embedded in the gateway for programming the Atmega 328P microcontroller and also to program the ESP8266 Wi-Fi module.

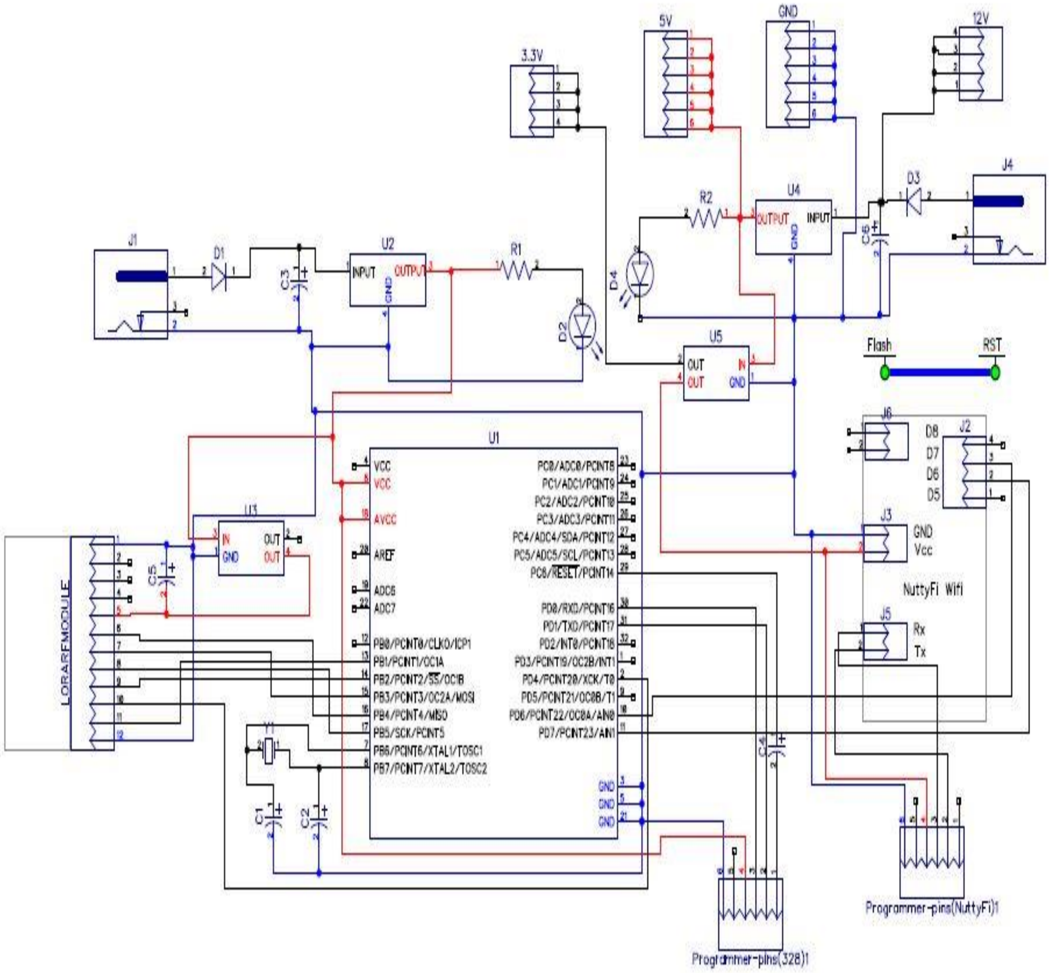

Figure 3.13 Circuit Diagram of the Gateway

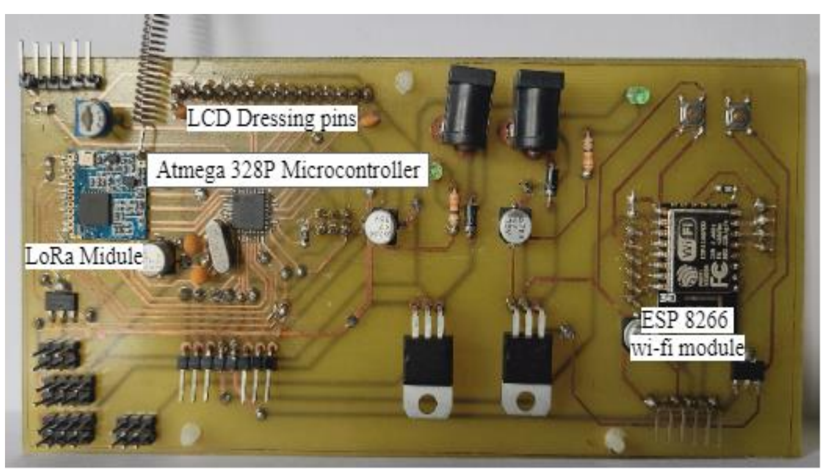

Figure 3.14 Gateway Prototype in Packaging

The prototype of the gateway is shown in figure 3.14. LoRa module, ATMega 328P microcontroller, ESP 8266 Wi-Fi module are highlighted on the gateway. The features of the customized gateway are presented in table.3.7.

Table 3.7 Features of Customized Gateway

Parameter	**Specifications**
Microcontroller	ATMega328P
Communication Module	SX1278 LoRa module [433 MHz-LPWAN), ESP8266 Wi-Fi module [2.4 GHz-LAN)]
Gnd	8 Pins
Voltage Converter	+3.3V and +5V
Power Trails	++12V (6 trails), +5V (8 trails) and +3.3V (6 trails)
Power Jack	2 [1 for ATmega 328P controller, 1 for ESP 8266 Wi-Fi module] +12V External power supply
Programming Pins	2 FTDI [ATmega 328P controller, 1 for ESP 8266 Wi-Fi module] and 1 ICSP
Display	LCD (20*4)

3.5 Chapter Summary

The chapter presents the system description of LoRa and blockchain-based waste management systems. The significance of a customized hardware prototype is discussed in detail, including the selection of each component that embedded in the sensor node and gateway. The circuit diagram of the sensor node and gateway is also presented in this chapter. The proteus model of the sensor node and gateway is also discussed along with the prototype of the sensor node and gateway. The customized IoT enabled hardware i.e., sensor node and gateway are designed to sense filling level of the bins on cloud server.

A research article is published about the customization of hardware and the **publication** is: Shaik Vaseem Akram, Rajesh Singh, Mohammed A. AlZain, Anita Gehlot, Mamoon

Rashid, Osama S. Faragallah, Walid El-Shafai, Deepak Prashar, "Performance Analysis of IoT and Long-Range Radio-Based Sensor Node and Gateway Architecture for Solid Waste Management is published in Sensors, MDPI (SCI).

Chapter 4

Performance Analysis of LoRa Network

In this chapter, the performance analysis of the LoRa network is discussed for evaluating the optimal parameters appropriate for the system implementation using LoRa. The significance of performance analysis and the explanation of distinct network parameters of the LoRa is discussed. A FLoRa simulation is performed for calculating the energy consumption of nodes by varying parameters like BW, SF, Tx power, number of nodes, and number of gateways with a carrier frequency of 433 MHz. The bit rate, time on-air (ToA), link budget, receiver sensitivity, and battery life of sensor node based on LoRa are evaluated by varying parameters like CR, BW, SF, Tx power, and payload size.

4.1 Performance Analysis

The performance analysis of the LoRa network enables the observation of the behavior of the network by varying different parameters like CR, BW, SF. Moreover, the performance analysis assists to finalize the parameters for the implementation of the system. Each parameter is considered for analyzing network behavior through evaluation metrics like bit rate, link budget, receiver sensitivity, ToA and battery life of LoRa enabled sensor node (Lavric et al., 2020).

- **Spreading Factor (SF)**

LoRa is based on the chirp spread spectrum, where chirps are the data carrier. The spreading factor affects the chirp rate, which in turn influences the transmission speed. Lower SF indicates high data transmission and vice versa. LoRa network uses a spreading factor for controlling the congestion during transmission. As the spreading factor is orthogonal, the signals modulating with various spreading factors can be transmitted on the same frequency channel at the same time without interference. LoRa modulation comprises six SFs from 7 to 12, where the SF shows an effect on the bit rate, ToA, and receiver sensitivity.

- **Bandwidth (BW)**

The frequency range in the spectrum band is represented by BW, which can be one of three bands: 500 kHz, 250 kHz, and 125 kHz. A higher bandwidth indicates fast transmission and lower bandwidth indicates long-distance transmission.

- **Code Rate**

The code rate is required for ensuring minimum interference during transmission. In data transmission, LoRa modulation incorporates forward error correction (FEC), which is attained by encoding 4-bit data with 5-bit, 6-bit, 7-bit, and 8-bit redundancies. The code rate is expressed in the equation (4.1):

$$CR = \frac{4}{4+n} \tag{4.1}$$

where ‘n’ ranges from 1 to 4

During data transmission, the code rate is proportional to transmission speed and is inversely related to ToA. A higher code rate indicates a faster transmission speed and a lower ToA.

- **LoRa Packet Structure**

LoRa packet structure consists of a preamble, optional header, payload, and Cyclic Redundancy Check (CRC) as shown in figure 4.1. A preamble is included to establish a link between transmitter and receiver. The header comprises the information and payload size of LoRa configuration, and it is encoded in the form of code rate = 4/8.

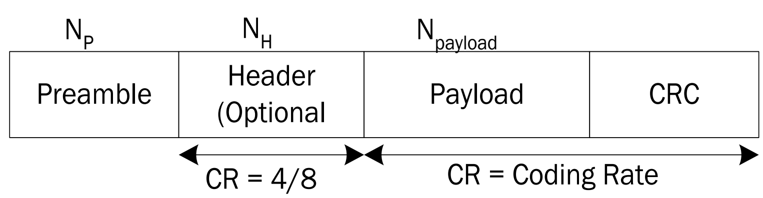

Figure 4.1 LoRa Packet Structure

In the packet structure, the payload encrypts with code rate, and in the last frame of the packet, the Cyclic Redundancy Check (CRC). LoRa packet duration is the integration of the transmitted packet and preamble. The preamble length is expressed in the equation (4.2.):

$$\text{Tpreamble} = (\text{npreamble} + 4.25)\text{Tsym} \quad (4.2)$$

Where $npreamble$ indicates programmed preamble length

The payload is defined by the enabled header mode and the number of payload symbols defined in equation (4.3):

$$n_{payload} = 8 + \max\left(ceil\left[\frac{(8PL - 4SF + 28 + 16RC - 20IH)}{4(SF - 2DE)}\right](CR + 4), 0\right) \quad (4.3)$$

where PL indicates a number of payload bytes; IH=0 during enabled header; IH=1 when no header is available; SF is spreading factor from 7 to 12; LowDataRateOptimize=1 for DE=1, DE=0 otherwise, CR indicates the code rate. The payload duration is estimated by multiplying the number of payload symbols by the symbol period and it is expressed in equation (4.4):

$$\text{Tpayload} = \text{npayload} * \text{Ts} \quad (4.4)$$

- **Time on Air (ToA)**

The amount of time taken for a signal to reach the receiver end from the transmitter is known as ToA. ToA of a packet is evaluated by integrating the spreading factor, code rate, and bandwidth. ToA of LoRa packet is the summation of payload duration and preamble and it is expressed in equation (4.5):

$$\text{Tpacket} = \text{Tpreamble} + \text{Tpayload} \quad (4.5)$$

Bit Rate/ data rate is defined as the number of bits that are transferred between transmitter and receiver. Bit rate (Rbit) of LoRa is expressed in equation (4.6):

$$Rbit = SF * \frac{BW}{2^{SF}} * C\text{R} \quad (4.6)$$

Where SF indicates spreading factor; BW indicates bandwidth and CR indicates code rate.

- **Receiver Sensitivity**

The ability of a system to extract information from signals is defined as receiver sensitivity. It can alternatively be characterized as the minimum signal strength that will enable the system to go into packet resolution mode. A variation in the receiver's temperature may influence the first term, which is generated by thermal noise in the 1-Hz bandwidth. The receiver noise figure (NF) is a constant for each hardware implementation. Finally, SNR denotes the signal-to-noise ratio necessary for the modulation technique beneath it. The signal-to-noise ratio and bandwidth are the design variables relevant to the LoRa designer. The LoRa receiver sensitivity (S) is calculated using equation (4.7):

$$\mathrm{S} = -174 + 10\log_{10} BW + \mathrm{NF} + \mathrm{SNR} \quad (4.7)$$

Where BW indicates bandwidth in kHz, SNR indicates Signal to Noise Ratio and NF indicates Noise fig. of a receiver in dB.

- **Signal-to-Noise Ratio (SNR)**

It is the ratio of the received power signal to the noise floor power level. SNR is often measured in the range of -20 dB to +10 dB. The received signal is less distorted if the range is approximately +10 dB. LoRa has an SNR range of -7.5 to -20 dB.

- **Link Budget**

The sum of all losses and gains from the transmitter to the receiver over free space is the link budget. (Ortín et al., 2018). The link budget can be computed using a simple model that includes transmitter power (PTx), antenna gain, receiver sensitivity (Rx), and free space path loss (FSPL). The link budget is expressed using equation (4.8):

$$\mathrm{PRx} = \mathrm{PTx} - \mathrm{L} + \mathrm{GTx} + \mathrm{GRx} \quad (4.8)$$

where PRx is received power or link budget (dBm), PTx indicates transmitter power(dBm), GRx indicates receiver antenna gain(dB), GTx indicates transmitting antenna gain (dB), and FSPL indicates free space path loss (dB).

FSPL is the amount of energy lost in free space during a conversation between the transmitter (Tx) and receiver (Rx). FSPL is derived from Friis transmission equation and Friis transmission equation (Balanis, 2012) is (4.9):

$$\frac{\mathrm{Pr}}{\mathrm{Pt}} = \left(\frac{\lambda}{4\pi \mathrm{R}}\right)^2 \quad G_{ot} \;\; G_{or} \tag{4.9}$$

where Pt and Pr denotes transmitted power and received power, λ denotes wavelength, and $G_{or} G_{ot}$ directivity of the receiving and transmitting antenna. As per FSPL's definition, the FSPL is expressed as equation (4.10):

$$\mathrm{FSPL} = \left(\frac{4\pi \mathrm{d}}{\lambda}\right)^2 \tag{4.10}$$

where d implies a distance between Tx and Rx (Meters); Tx implies transmitter; Rx implies receiver, and λ indicates wavelength. The wavelength (λ) is expressed in the equation (4.11)

$$\lambda = \frac{\mathrm{c}}{\mathrm{f}} \; ; \; \mathrm{c} \; = \; 3 \; * 10^8 \; \mathrm{m/s} \tag{4.11}$$

4.2 FLoRa Simulation

FLoRa is a platform to create a LoRa network by providing modules for LoRa nodes, gateways, and network servers (*Home | FLoRa - A Framework for LoRa simulations*, n.d.). By using Adaptive Data Rate (ADR), the network server and nodes can adjust configuration parameters can be adjusted dynamically. Through Adaptive Data Rate, the network server and nodes offer dynamic management of configuration parameters (ADR). Statistics on energy use can be gathered for each node. The FLoRa simulation is performed to evaluate the energy consumption of the nodes by varying the distinct parameters. The evaluation of energy consumption of nodes facilities to calculate optimal parameters that are optimal for the implementation of the system. FLoRa is based on the OMNeT++ discrete event simulation library (Bouras et al., 2019). FLoRa is built on the OMNeT++ framework, which is integrated with the INET Framework that enables experimentation of distinct network protocols (*OMNeT++ Discrete Event Simulator*, n.d.). Furthermore, the

FLoRa structure provides appropriate LoRaWAN architecture(*Home | FLoRa - A Framework for LoRa simulations*, n.d.) implementation as well as a reliable LoRa radio physical layer model based on past experimental findings (Slabicki et al., 2018). Using the FLoRa architecture, it is feasible to simulate the entire LoRaWAN star-topology architecture, which consists of four entities: LoRa nodes, gateways, a network server, and an application server (Petajajarvi et al., 2015).

Figure 4.2 illustrates the working model of the FLoRa functioning model, in which the complete network is deployed according to the LoRa architecture. Figure 4.3 illustrates the working of the FLoRa simulation, in which the LoRa nodes are transmitting information to the cloud via LoRa, and a Wi-Fi-enabled gateway. Figure 4.4 shows the two nested submodules that deal with the LoRa network service (LoRaNic), and application layer (simpleLoRaApp). The network module (LoRaNic) and the application module (LoRaNode) are both present in the LoRaNode module (simpleLoRaApp). The LoRaNic module includes a LoRa network, a radio module (LoRaRadio), and a MAC module (LoRaMAC). LoRaNode is the major module in which parameters are varying for evaluating the behavior of the LoRa network of waste management and it is shown in figure 4.4. In the simulation, the parameters are configured to evaluate the energy consumption of nodes are BW = 125 kHz; carrier frequency = 433 MHz; CR = 4; SF = 7; No of packets = 2; gateway distance = 320 m; network size = 480 m 480; number of gateways =1; number of nodes =4, and deployment type = square. The simulation is performed in four different cases, by varying the parameters.

- **Case ‘1’**

In case ‘1,' the code rate is varied from 1 to 4 and no significant variation is observed in the energy consumption of the LoRa node. The LoRa node's Tx power is varied from 2, 5, 8, 11, and 14 dBm to check the change in energy consumption. The tx power is represented with Tx1, Tx2, Tx3, Tx4, and Tx5 The remaining parameters, such as carrier frequency, spreading factor, bandwidth, no of packets, network size, and gateway distance is kept constant.

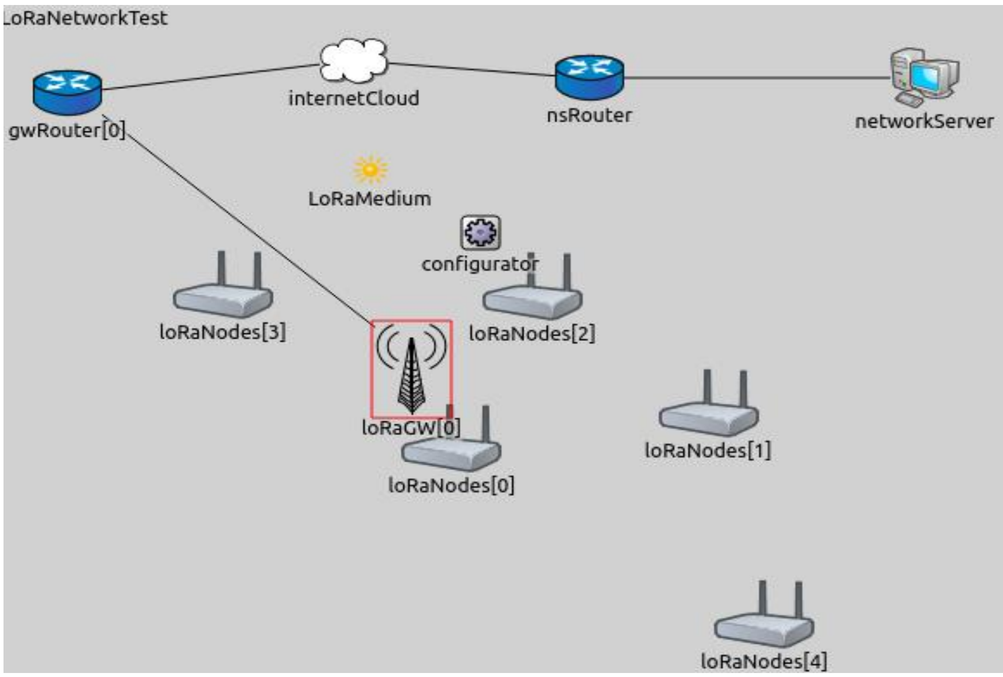

Figure 4.2 FLoRa Simulation Graphical User Interface

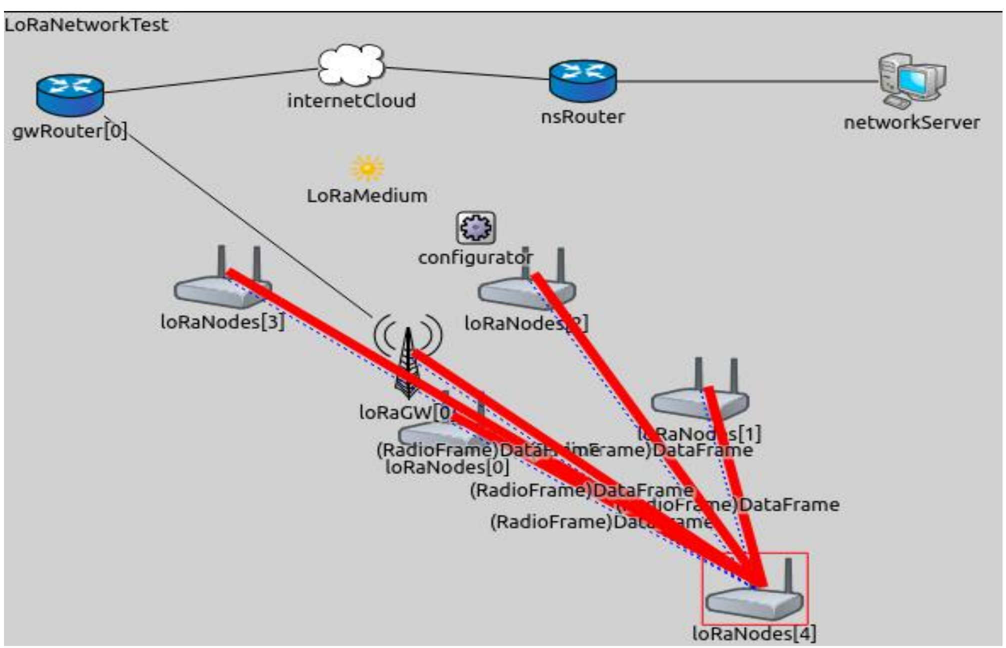

Figure 4.3 Working Model in FLoRa Simulation

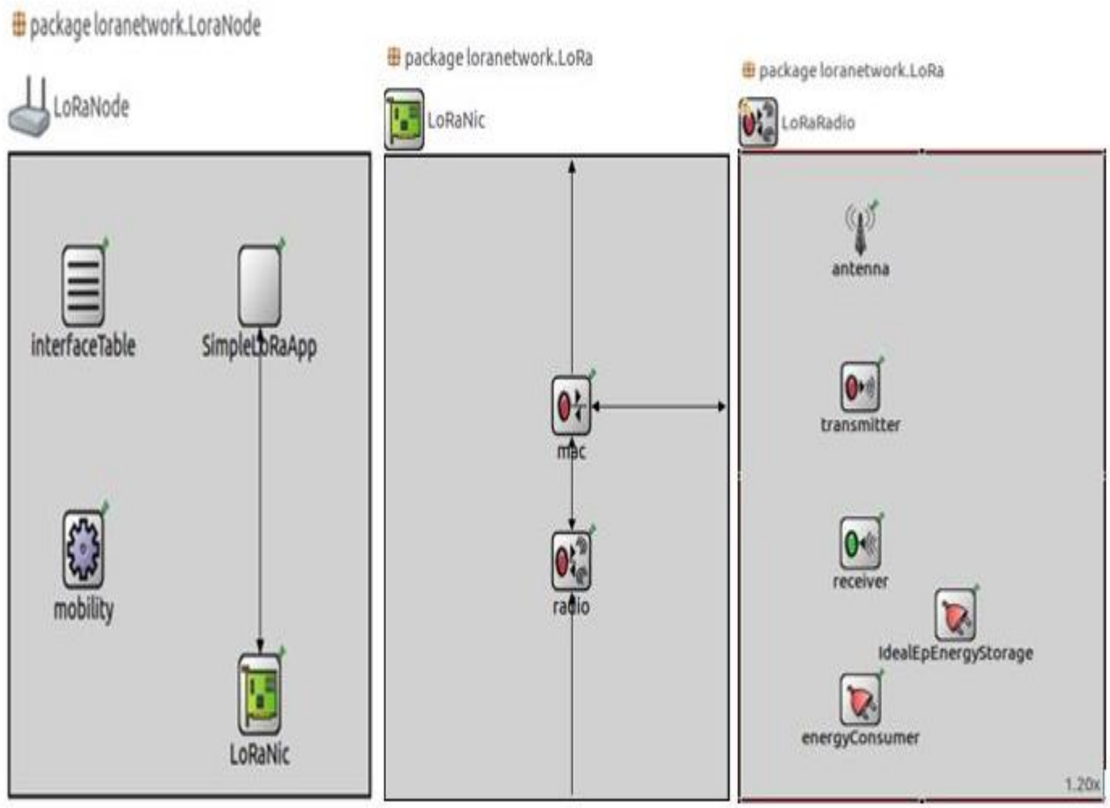

Figure 4.4 Two Nested Submodules

The 4 nodes are represented as Node ‘1', Node ‘2', Node ‘3', and Node ‘4'. The simulation is performed for four nodes by varying transmission power and energy consumption of four nodes recorded in table 4.1.

The simulation results demonstrate that for Tx power of 2 and 5 dBm, node ‘1' and node ‘2' consume the same amount of energy. At the Tx power of 11 dBm, the energy consumption of node ‘2' gradually decreases. At a Tx power of 8 dBm, the energy consumption of node ‘3' immediately rises from 1.90 mW to 2.74 mW. When the Tx power is configured to 2 or 5 dBm, Node ‘4' consumes a consistent amount of energy; however, when the Tx power is set to 8 dBm, the energy consumption rises and then reduces to 2.31 mW. Figure 4.5 illustrates that node ‘3' (red color line) consumes the maximum energy of all nodes when the Tx power is tuned to 8 dBm.

Table 4.1 Energy Consumption in case '1' for Tx power 2 dBm-14dBm

Node Number	Energy Consumption at 2 dBm (mW)	Energy Consumption at 5 dBm (mW)	Energy Consumption at 8 dBm (mW)	Energy Consumption at 11 dBm (mW)	Energy Consumption at 14 dBm (mW)
Node '1'	2.45	2.46	2.46	2.09	2.18
Node '2'	2.45	2.46	2.18	1.95	2.03
Node '3'	1.89	1.90	2.74	3.10	3.24
Node '4'	2.38	2.39	2.60	2.31	2.41

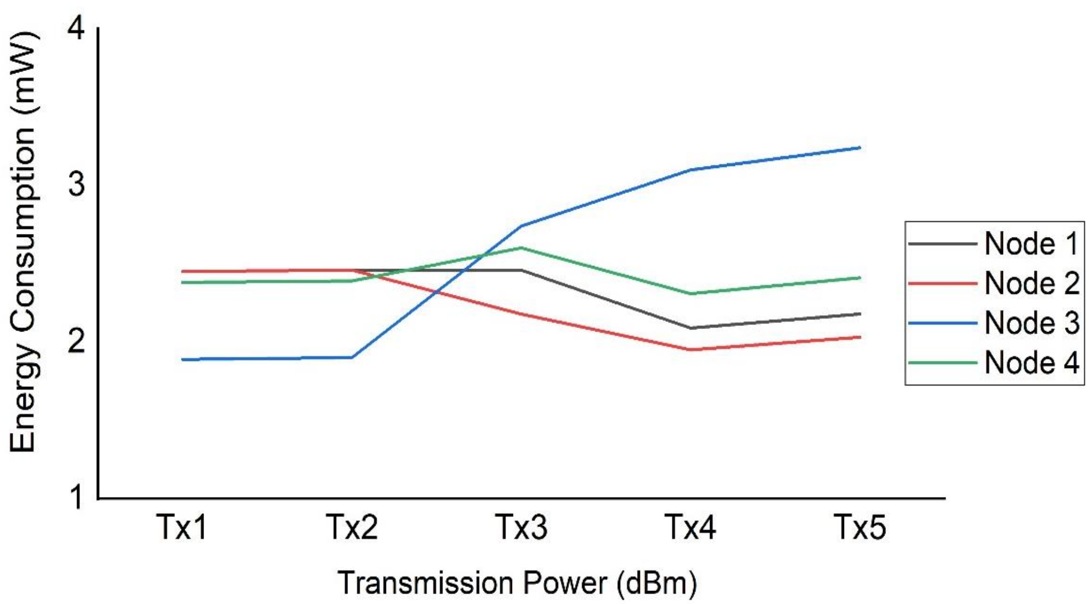

Figure 4.5 Nodes Energy Consumption in Case '1' for Tx power 2 dBm-14dBm

- **Case '2'**

In case '2', the simulation is performed by increasing the number of gateways = 2 and maintaining all other parameters constant. The energy consumption of four nodes is shown in Table 4.2. At the Tx level of 2 dBm, the energy consumption of all nodes rapidly decreased as the number of gateways increased to two. When compared to a single gateway implementation in the simulation, the energy consumption of Node ‘1 decreases for the Tx power of 2 dBm, 5 dBm, and 8 dBm as shown in figure 4.4. The energy consumption of node ‘4’ is maximum at Tx power of 14 dBm and at remaining Tx powers the energy consumption of node ‘4’ is decreased. In Node ‘3’, the energy consumption of nodes is maximum for the Tx power of 2dBm and 5 dBm.

Table 4.2 Energy Consumption in case ‘2’ for Tx power 2 dBm-14dBm

Node Number	Energy Consumption at 2 dBm (mW)	Energy Consumption at 5 dBm (mW)	Energy Consumption at 8 dBm (mW)	Energy Consumption at 11 dBm (mW)	Energy Consumption at 14 dBm (mW)
Node ‘1’	1.68	1.69	2.39	2.10	2.78
Node ‘2’	2.10	2.11	2.53	2.81	2.03
Node ‘3’	2.10	2.12	2.60	2.52	2.63
Node ‘4’	2.24	2.25	2.39	2.24	3.69

- **Case ‘3’**

In case ‘3’, the number of nodes is expanded to 8 and the remaining parameters of the simulation are maintained the same as mentioned in case ‘1’. The representation of 8 nodes is as: Node ‘1, Node ‘2’, Node ‘3’, Node ‘4’, Node ‘5’, Node ‘6’, Node ‘7’, and Node ‘8’. The simulation is performed with the same parameters and the energy consumption of nodes is presented in table 4.3. In comparison to the previous case, the amount of energy consumed by the first four nodes is varied and as shown in figure 4.7. Node ‘1' has consumed a high portion of energy at 11 dBm, i.e., 3.25 dBm, while Node ‘2' has consumed a moderate amount of energy at 5 dBm, i.e., 1.61 dBm.

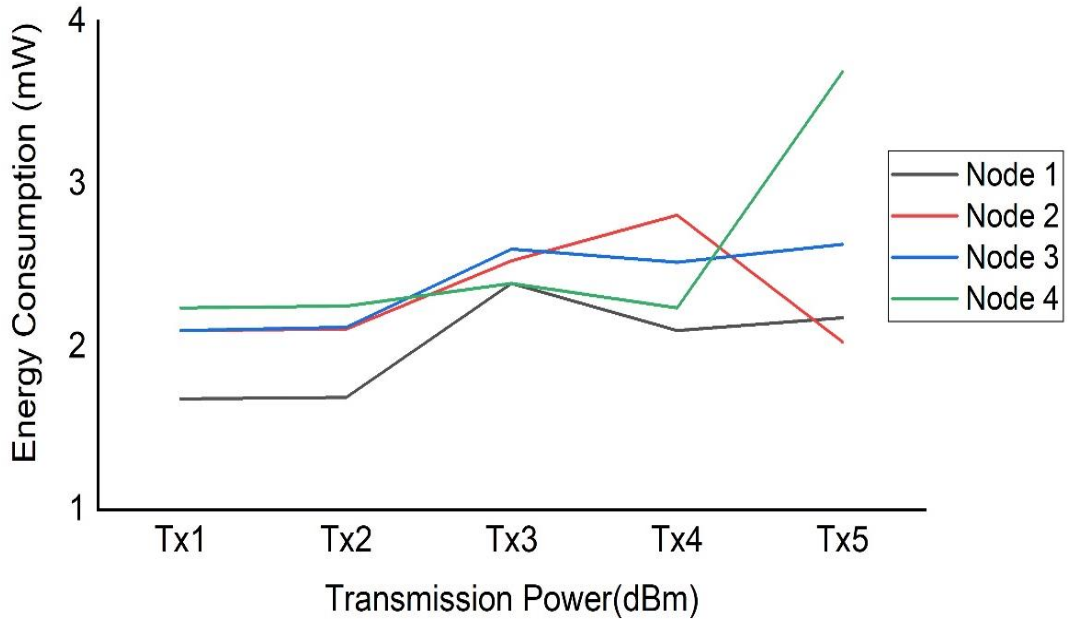

Figure 4.6 Nodes Energy Consumption in Case '2' for Tx power 2 dBm-14dBm

At 14 dBm Tx power, the energy consumption for Nodes '2', '3', and '4' is similar, i.e., 1.88 mW and the energy consumption for nodes '5' and '6' is the same i.e., 2.48 mW. The energy consumption of Node '3' gradually reduces from 3.01 mW to 1.88 mW. Node '5' energy consumption is progressively increased from 2.03 mW to 2.48 mW, while Node '8' energy consumption also increased from 1.96mW to 2.56mW.

- **Case '4':**

In case '4', the number of nodes increased to '16, and the remaining parameters are maintained constant. Node '1', Node '2', Node '3', Node '4', Node '5', Node '6', Node '7', Node '8', Node '9', Node '10', Node '11', Node '12', Node '13', Node '14', Node '15', and Node '16' are representation of 16 nodes. After performing the simulation with their parameters, the energy consumption of 16 nodes is shown in table 4.4. The high energy consumption of nodes is acquired at Tx of 11 dBm for the Node '13' is 3.10 mW, while the low energy consumption of nodes is recorded at Tx power of 14 dBm for the Node '10', i.e., is 1.73 mW.

Table 4.3 Energy Consumption in case '3' for Tx power 2 dBm-14dBm

Node Number	Energy Consumption at 2 dBm (mW)	Energy Consumption at 5 dBm (mW)	Energy Consumption at 8 dBm (mW)	Energy Consumption at 11 dBm (mW)	Energy Consumption at 14 dBm (mW)
Node '1'	1.75	1.76	2.04	3.25	1.95
Node '2'	1.61	1.59	2.32	1.95	1.88
Node '3'	3.01	3.02	2.88	1.95	1.88
Node '4'	2.52	2.53	2.11	2.38	1.88
Node '5'	2.03	2.04	2.04	2.09	2.48
Node '6'	2.51	2.46	2.74	2.74	2.48
Node '7'	2.17	2.18	1.83	2.74	2.33
Node '8'	1.96	1.97	2.11	2.31	2.56

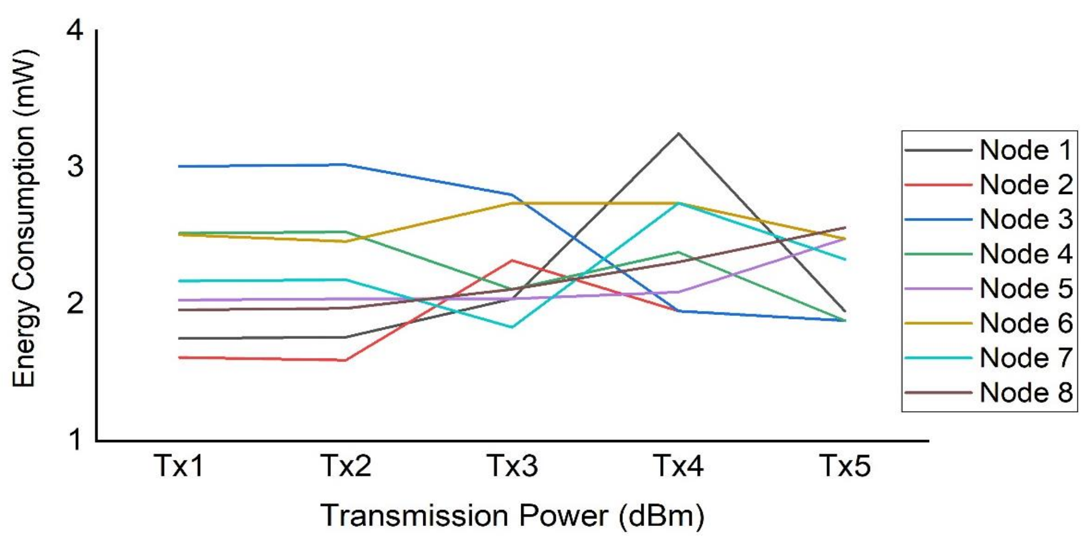

Figure 4.7 Nodes Energy Consumption in Case '4' for Tx power 2 dBm-14dBm

Table 4.4 Energy Consumption (E.C) in case '4' from Tx power 2 dBm to 14dBm

Node Number	Energy Consumption at 2 dBm (mW)	Energy Consumption at 5 dBm (mW)	Energy Consumption at 8 dBm (mW)	Energy Consumption at 11 dBm (mW)	Energy Consumption at 14 dBm (mW)
Node '1'	2.11	2.11	2.53	2.81	2.71
Node '2'	1.96	1.97	2.26	2.46	2.26
Node '3'	1.82	1.83	2.81	2.09	2.86
Node '4'	2.66	2.67	3.17	2.31	2.71
Node '5'	1.89	1.90	1.89	2.46	3.08
Node '6'	2.38	2.39	2.39	2.09	1.88
Node '7'	2.31	2.32	2.53	1.96	2.86
Node '8'	2.09	2.04	2.32	2.74	2.26
Node '9'	1.89	1.90	3.10	2.60	3.31
Node '10'	2.60	2.61	2.67	2.64	1.73
Node '11'	2.03	2.04	2.60	2.45	2.18
Node '12'	1.75	1.76	1.90	2.60	2.03
Node '13'	2.80	2.81	1.76	3.10	2.78
Node '14'	1.96	1.97	2.74	2.09	2.63

Node '15'	2.03	1.97	2.46	2.52	2.48
Node '16'	2.38	2.39	2.82	2.81	2.33

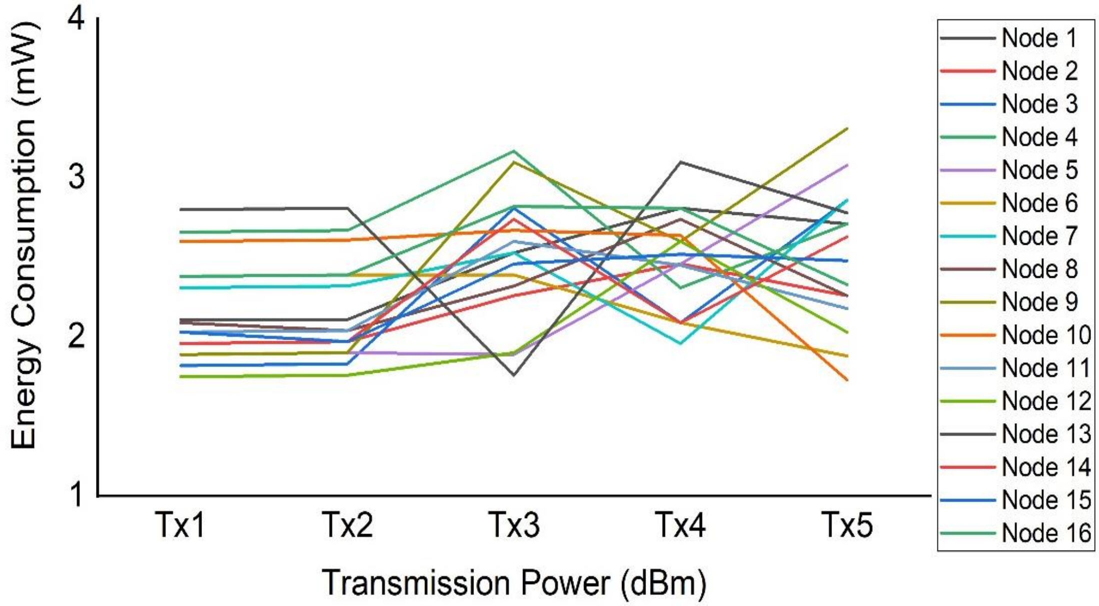

Figure 4.8 Nodes Energy Consumption in Case '4' for Tx power 2 dBm-14dBm

4.3 Performance Analysis

In this section, the performance analysis of the distinct evaluation metrics of LoRa is performed by varying SFs, CR, payload, and BW.

4.3.1 Bit Rate

The data rate/bit rate is defined as the number of bits transferred between the transmitter and receiver during communication. The input parameters SF, CR, and BW are incorporated for evaluating the LoRa data rate. The data rate is expressed in bits per second (bps). Equation 4.6 is used for calculating the bit rate from SF 7-12. Six cases are divided for calculating the bit rate for 6 SFs. In the first case, the parameters such as SF 7, BW (7.5kHz to 500 kHz), and CR (1 to 4) are used for calculating the bit rate.

Figure 4.9 illustrates the graph of bit rate at SF 7, and the graph concludes that the bit rate is low (213 bps) at BW 1 (7.5 kHz) and code rate 4. The high bit rate (21875 bps) is observed at BW 10 (500 kHz) and code rate 1.

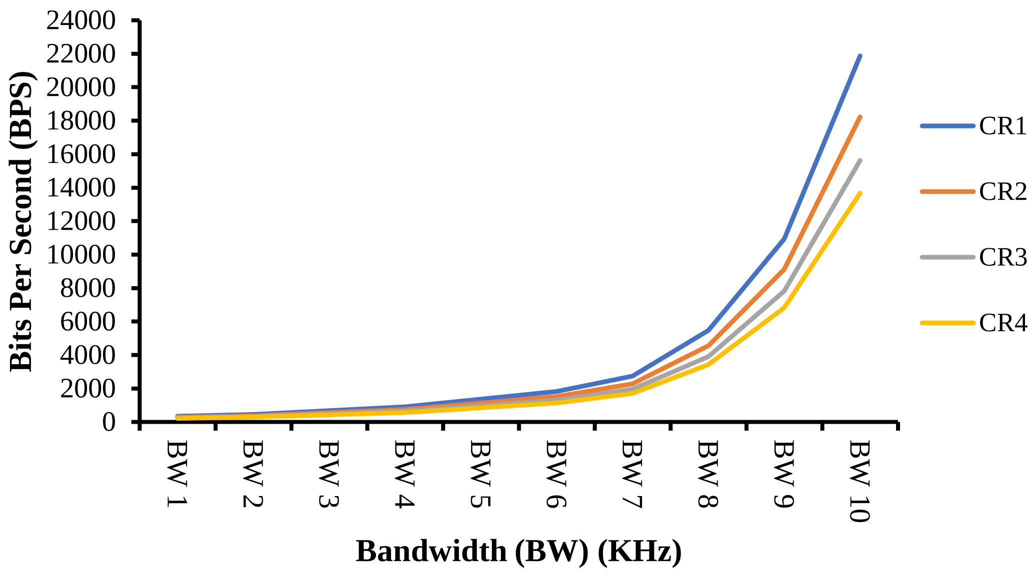

Figure 4.9 Bit Rate Analysis for Different code rate and bandwidth with SF 7

In the second case, the parameters such as SF 8, BW (7.5kHz to 500 kHz), and CR (1 to 4) are used for calculating the bit rate. Figure 4.10 illustrates the graph of bit rate at SF 8, and the graph concludes that the bit rate is low (121 bps) at BW 1 (7.5 kHz) and code rate 4. The high bit rate (12500 bps) is observed at BW 10 (500 kHz) and code rate 1.

In the third case, the parameters such as SF 9, BW (7.5kHz to 500 kHz), and CR (1 to 4) are used for calculating the bit rate. Figure 4.11 illustrates the graph of bit rate at SF 9, and the graph concludes that the bit rate is low (68 bps) at BW 1 (7.5 kHz) and CR 4. The high bit rate (7031 bps) is observed at BW 10 (500 kHz) and code rate 1.

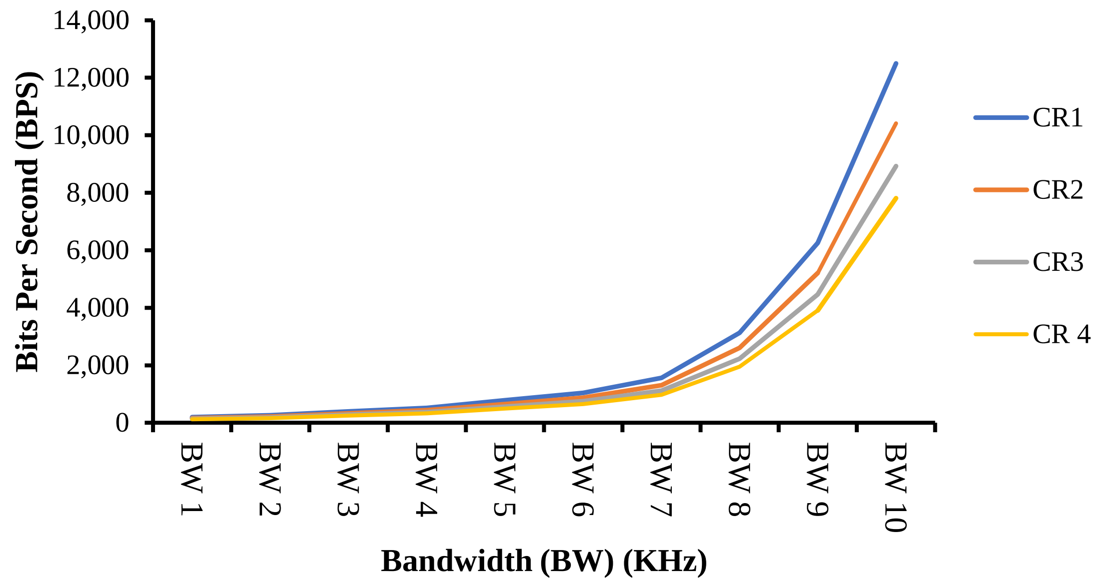

Figure 4.10 Bit Rate Analysis for Different code rate and bandwidth with SF 8

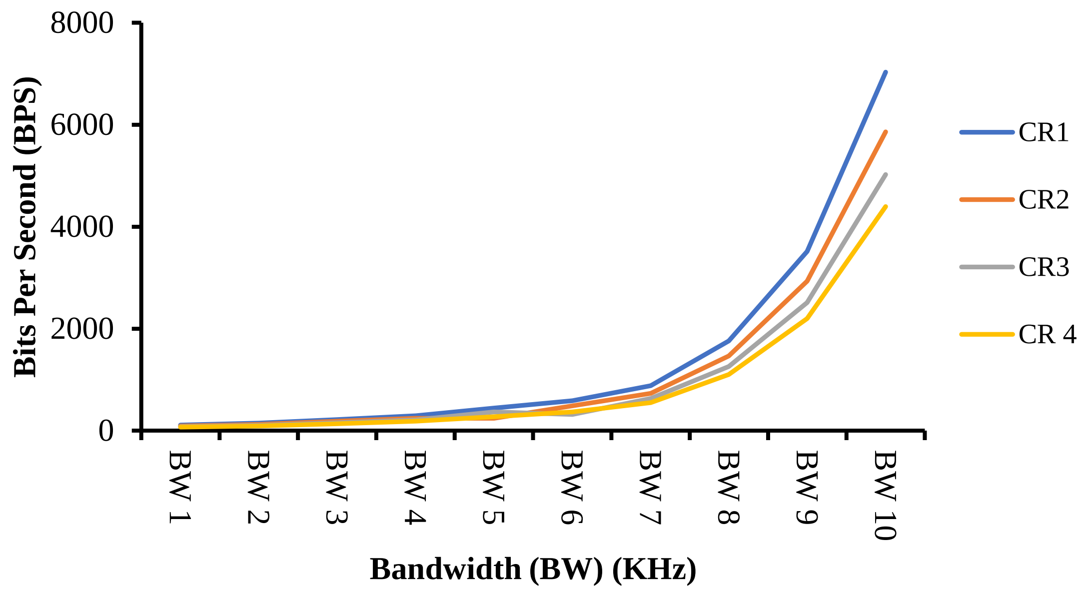

Figure 4.11 Bit Rate Analysis for Different code rate and bandwidth with SF 9

In the fourth case the parameters such as SF 10, BW (7.5kHz to 500 kHz), and CR (1 to 4) are used for calculating the bit rate. Figure 4.12 illustrates the graph of bit rate at SF 10, and the graph concludes that the bit rate is low (38 bps) at BW 1 (7.5 kHz) and CR 4. The high bit rate (3096 bps) is observed at BW 10 (500 kHz) and code rate 1.

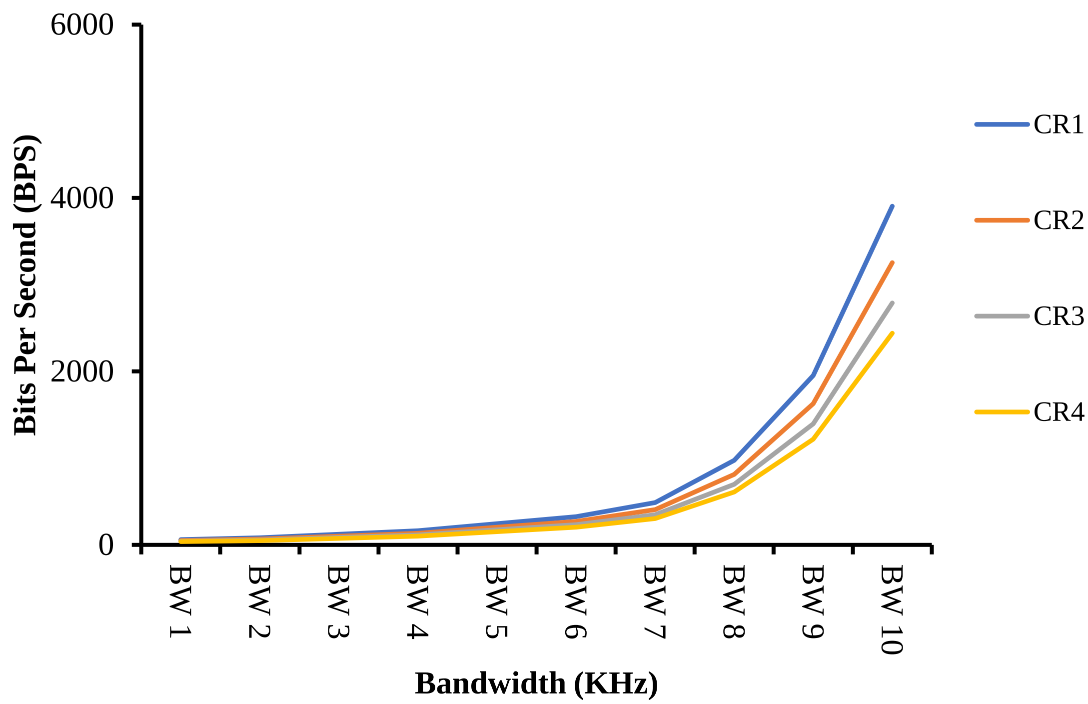

Figure 4.12 Bit Rate Analysis for Different code rate and bandwidth with SF 10

In the fifth case, the parameters such as SF 11, BW (7.5kHz to 500 kHz), and CR (1 to 4) are used for calculating the bit rate. Figure 4.13 illustrates the graph of bit rate at SF 11, and the graph concludes that the bit rate is low (20 bps) at BW 1 (7.5 kHz) and code rate 4. The high bit rate (2148 bps) is observed at BW 10 (500 kHz) and CR1.

In the sixth case, the parameters such as SF 12, BW (7.5kHz to 500 kHz), and CR (1 to 4) are used for calculating the bit rate. Figure 4.14 illustrates the graph of bit rate at SF 12, and the graph concludes that the bit rate is low (11 bps) at BW 1 (7.5 kHz) and code rate 4. The high bit rate (1171 bps) is observed at BW 10 (500 kHz) and CR 1.

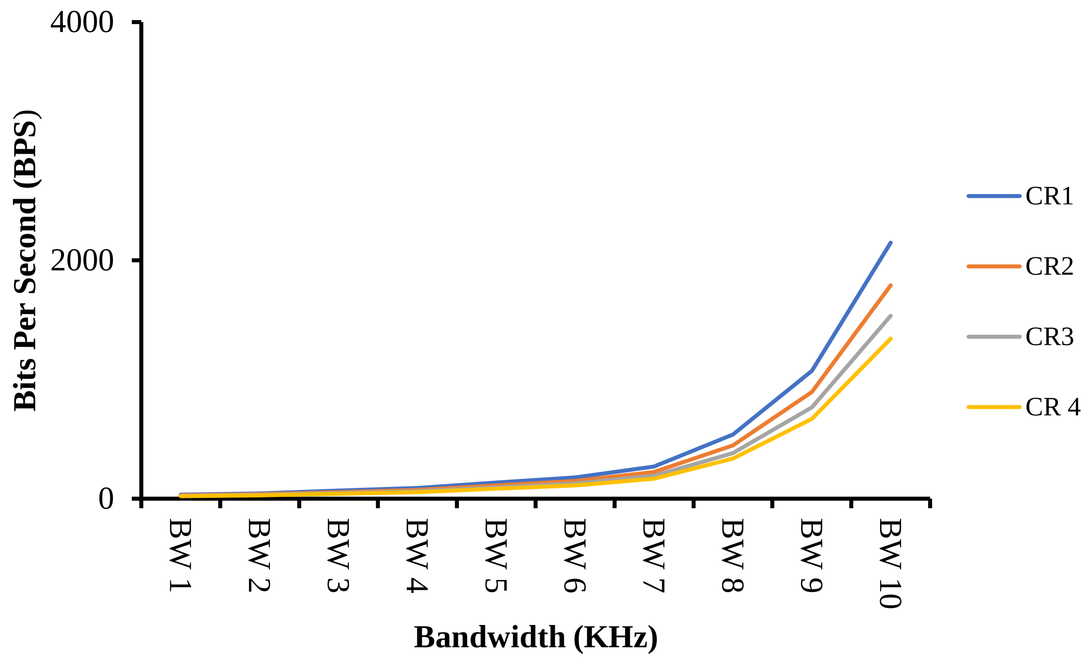

Figure 4.13 Bit Rate Analysis for Different code rate and bandwidth with SF 11

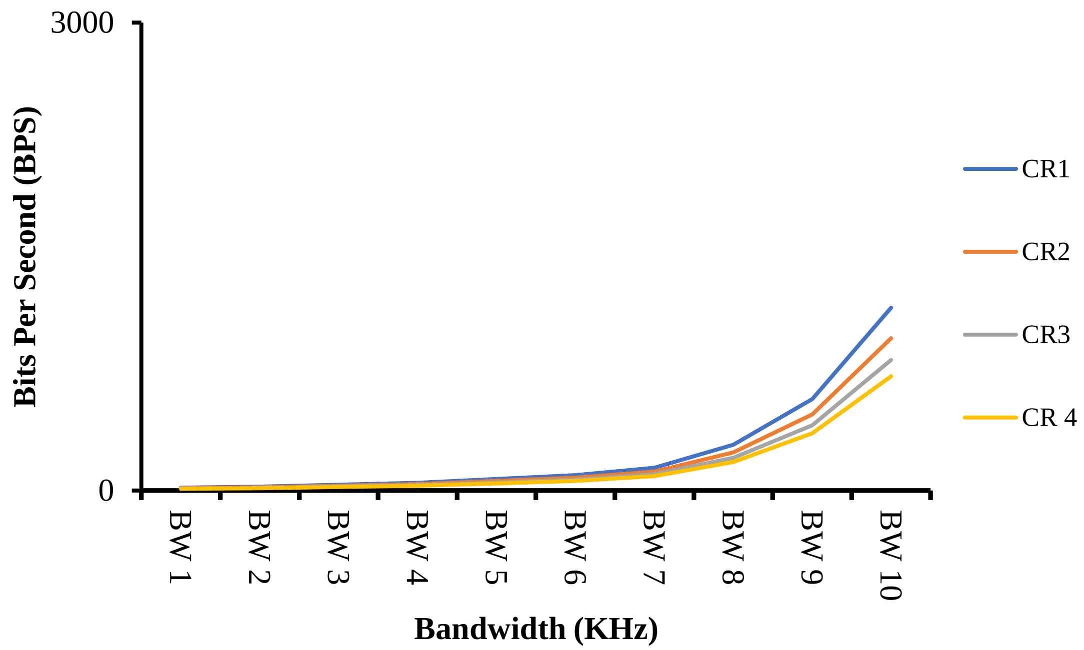

Figure 4.14 Bit Rate Analysis for Different code rate and bandwidth with SF 12

4.3.2 LoRa Sensitivity

The SF, noise figure, and BW are the input parameters for determining the LoRa sensitivity of the receiver. In this case, the Noise fig. (SNR) value varies depending on the spreading factor. The SNR of the spreading factor 7 is -7.5dB, the SNR of the spreading factor 8 is -10 dB, the SNR of the spreading factor 9 is -12.5 dB, the SNR of the spreading factor 10 is -15 dB, the SNR of the spreading factor 11 is -17.5 dB, and the SNR of the spreading factor 12 is -20 dB.

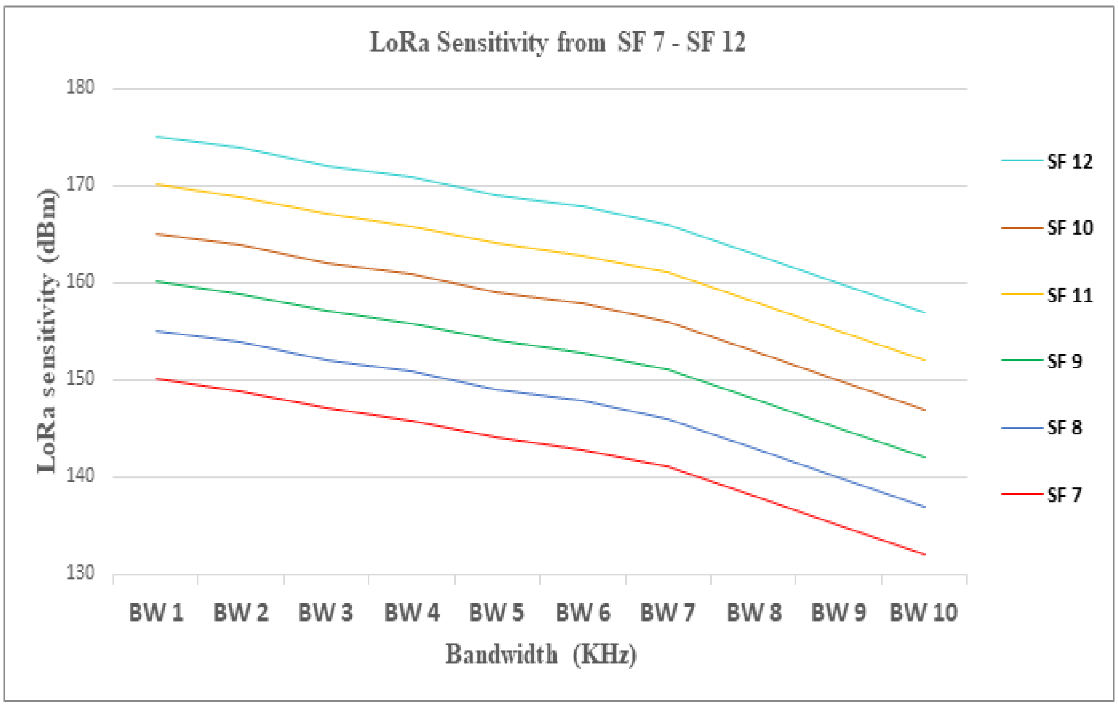

Figure 4.15 LoRa Sensitivity from SF (7– 12)

The BW considered during evaluation of receiver sensitivity are as follows: 7.8 kHz (BW1); 10.4 kHz (BW2); 15.6 kHz (BW3); 20.8 kHz (BW4); 31.2 kHz (BW5); 41.7 kHz (BW6); 62.5 kHz (BW7); 125 kHz (BW8); 250 kHz (BW9); and 500 kHz (BW10). The receiver sensitivity is expressed in a negative value, such as -127 dBm, and any value above this indicates that sensitivity is declining. Figure 4.15 illustrates that the sensitivity power for the SF 7 is largest at BW 10 (500 kHz), and the sensitivity for the SF 12 is lowest at

BW 1 (7.5 kHz). Following the BW 4, the sensitivity of each spreading factor gradually increases (20.8 kHz).

4.3.3 Time on Air (ToA)

The amount of time taken for a signal to reach the receiver end from the transmitter is known as ToA. The calculation of the ToA with following parameters, preamble = 8 symbols, payload = 25 bytes, Tx power = 14 dBm and carrier frequency = 433 MHz. The three bandwidths 125 kHz (BW 1), 250 kHz (BW 2), and 500 kHz (BW 3) are considered along with SF from 7 to 12, and code rate from 1 to 4. In equation 4.6, the SF and BWhave multiple values, so the ToA calculation is done in four cases. The cases are categorized on the basis of CR (1 to 4). In the first case, the calculation of ToA is carried out with parameters CR =1, SF 7 to 12, and BW 125kHz, 250 kHz, and 500kHz. The calculated results of the first case are shown in table 4.5.

It has been observed that the ToA for SF 7 and CR 1 is 56.58 milliseconds (ms), and ToA for SF 12 and BW 1 is 1318.71 ms. ToA is increased along with an increase in SF and decreases with an increase in BW. The X-axis of the graph denotes the SF and Y-axis denotes the ToA. The graph (figure 4.16) concludes that the ToA increase after the SF 8 and reached maximum at SF12.

Table 4.5 Time on Air (ms) for different SF and BW with CR = 1

Spreading Factor	Bandwidth ‘1’	Bandwidth ‘2’	Bandwidth 3'
Spreading Factor 7	56.58	28.29	14.14
Spreading Factor 8	102.91	51.46	25.73
Spreading Factor 9	205.82	102.91	51.46
Spreading Factor 10	370.69	185.34	92.67
Spreading Factor 11	741.38	370.69	185.34
Spreading Factor 12	1318.91	659.46	329.73

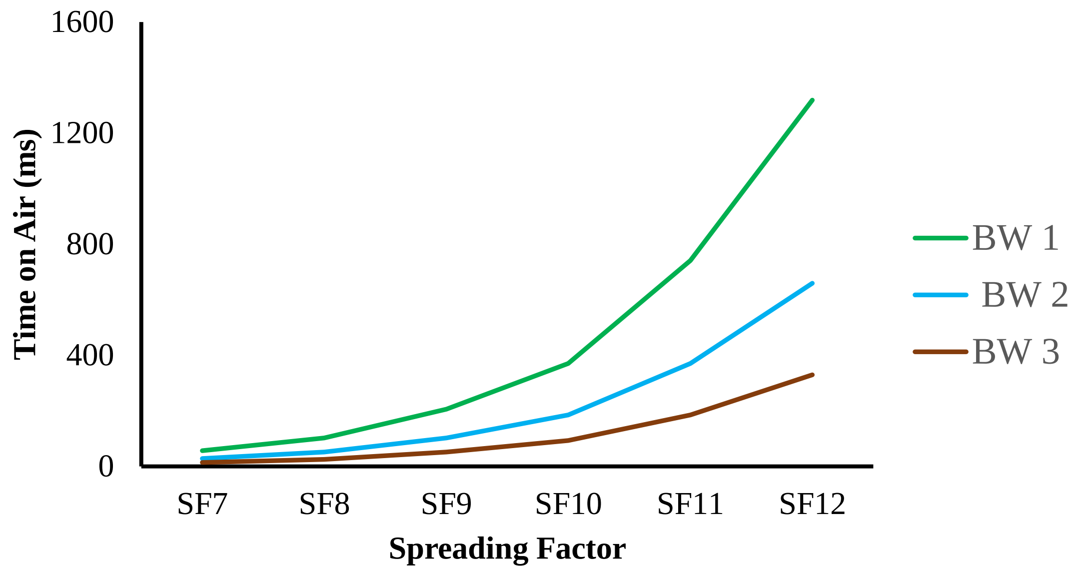

Figure 4.16 Time on Air (ms) for different SF and BW with CR = 1

In the second case, the calculation of ToA is carried out with parameters CR =2, SF 7 to 12, and BW 125kHz, 250 kHz, and 500kHz. The calculated results of the second case are shown in table 4.6. It has been observed that the ToA for SF7 and BW 1 is 63.74 milliseconds (ms), and ToA for SF 7 and BW3 is 15.94 ms. From the results, it is concluded ToA is the maximum for SF 12 and BW1. ToA is minimum for SF 7 and BW3. The graph (figure 4.17) concludes that the ToA increases after the spreading factor 8 and reached the maximum for spreading factor 12 and BW1.

Table 4.6 Time on Air (ms) for different SF and BW with CR = 2

Spreading Factor	Bandwidth '1'	Bandwidth '2'	Bandwidth 3'
Spreading Factor 7	63.74	31.87	15.94
Spreading Factor 8	115.2	57.6	28.8
Spreading Factor 9	230.4	115.2	57.6
Spreading Factor 10	411.65	205.82	102.91
Spreading Factor 11	823.3	411.65	205.82
Spreading Factor 12	1449.9	724.99	362.5

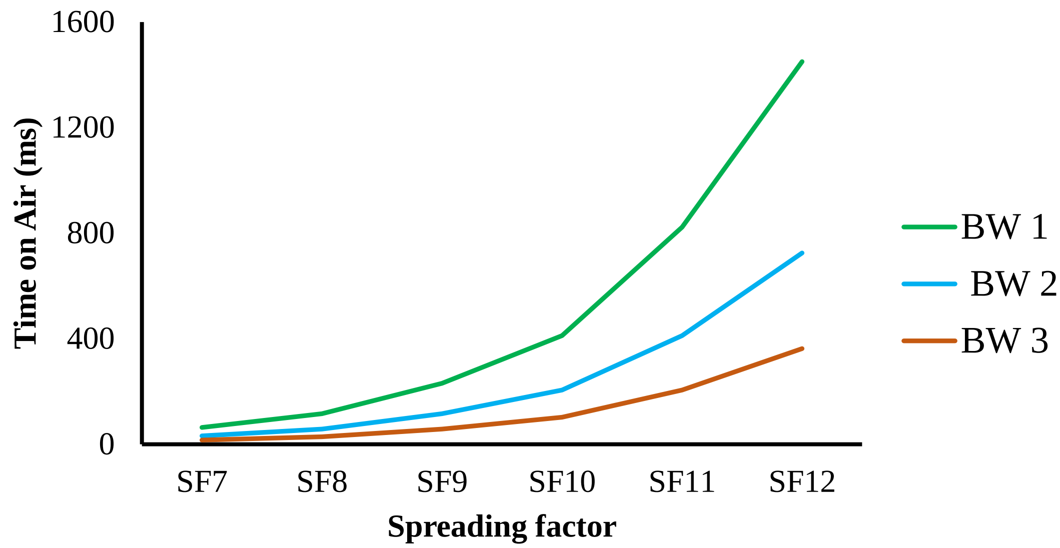

Figure 4.17 Time on Air (ms) for SF and BW with CR = 2

In the third case, the calculation of ToA is carried out with parameters code rate =3, spreading factor 7 to 12, and BW 125kHz, 250 kHz, and 500kHz. The calculated results of the third case are shown in table 4.7. It has been observed that the ToA for spreading factor 7 and BW 1 is 70.91 milliseconds (ms), and ToA for spreading factor 7 and BW3 is 17.73ms. From the results, it is concluded ToA is the maximum for spreading factor 12 and BW1. ToA is minimum for spreading factor 7 and BW3. The graph (figure 4.18) concludes that the ToA increases after the spreading factor 8 and reached a maximum for spreading factor 12 and BW1.

Table 4.7 Time on Air (ms) for different SF and BW with CR = 3

Spreading Factor	Bandwidth '1'	Bandwidth '2'	Bandwidth 3'
Spreading Factor 7	70.91	35.46	17.73
Spreading Factor 8	127.49	63.74	31.87
Spreading Factor 9	254.98	127.49	63.74
Spreading Factor 10	452.61	226.3	113.15
Spreading Factor 11	905.22	452.61	226.3
Spreading Factor 12	1581.06	790.53	395.26

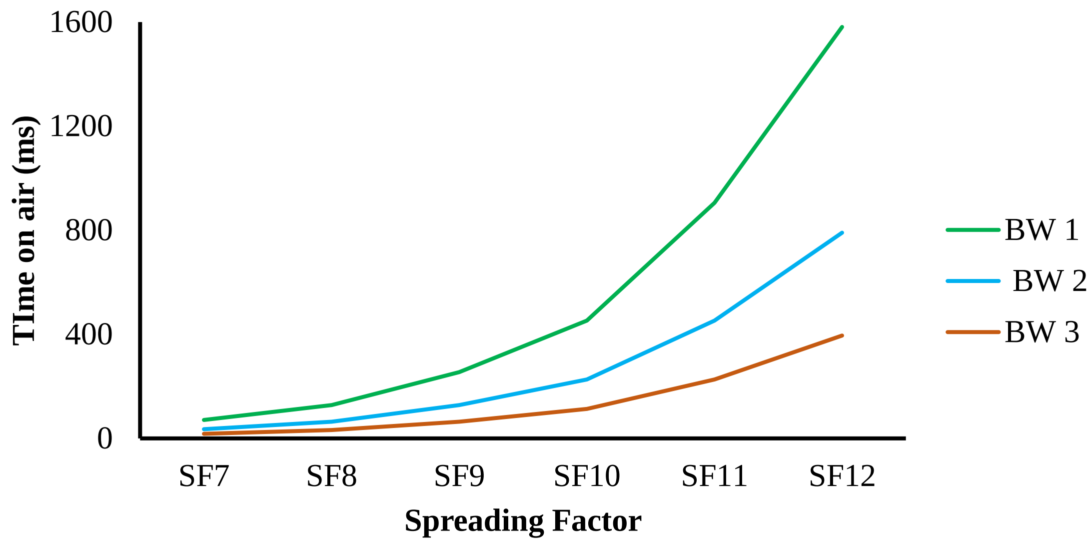

Figure 4.18 Time on Air (ms) for different SF and BW with CR = 3

Table 4.8 Time on Air (ms) for different SF and BW with CR = 4

Spreading Factor	**Bandwidth '1'**	**Bandwidth '2'**	**Bandwidth 3'**
Spreading Factor 7	78.08	39.04	19.52
Spreading Factor 8	139.78	69.89	34.94
Spreading Factor 9	279.55	139.78	69.89
Spreading Factor 10	493.57	246.78	123.39
Spreading Factor 11	987.14	493.57	246.78
Spreading Factor 12	1712.13	856.06	428.03

In the fourth case, the calculation of ToA is carried out with parameters code rate =4, SF 7 to 12, and BW 125kHz, 250 kHz, and 500kHz. The calculated results of the third case are shown in table 4.8. It has been observed that the ToA for SF7 and BW 1 is 78.08 milli seconds (ms), and ToA for SF7 and BW3 is 19.52 ms. From the results, it is concluded ToA is maximum for SF 12 and BW1. ToA is minimum for SF7 and BW3. The graph (figure 4.18) concludes that the ToA increases after the SF 8 and reached maximum for SF12 and BW1. From the four cases, the maximum ToA is recorded in the fourth case at SF12 and BW1 (125 kHz). The minimum ToA is recorded in the first case at SF7 and BW3

(500kHz). The CR is directly related to the rise in ToA; for example, at CR 1, the ToA of BW 1 is 56.58 ms, whereas, at CR 4, the ToA is 78.08 ms.

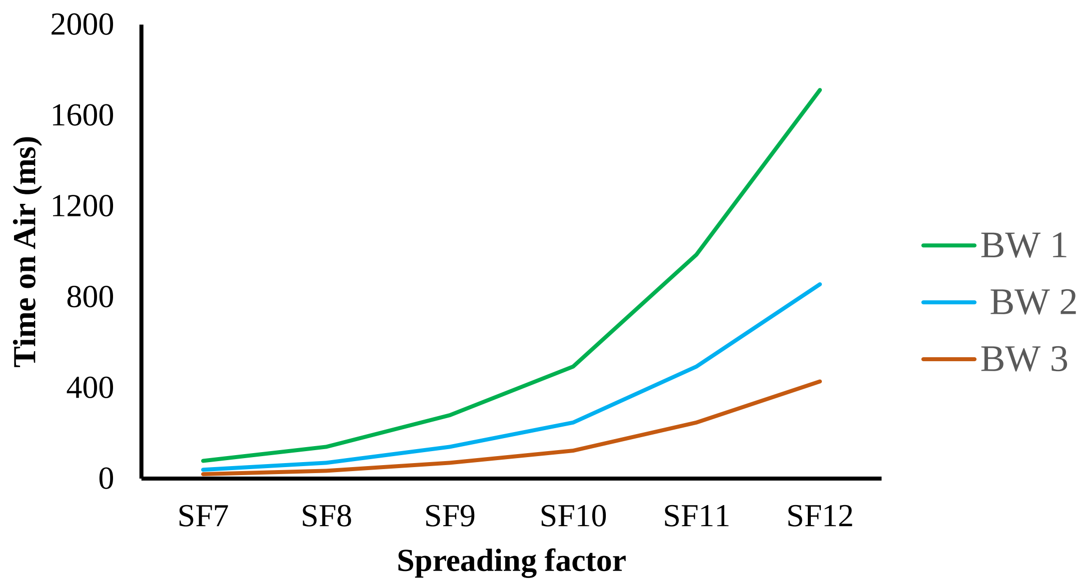

Figure 4.19 Time on Air (ms) for different SF and BW with CR = 4

4.3.4 Link Budget

The link budget is the summation of the gains and losses during the transmission of a signal from transmitter to receiver. The link budget is evaluated by considering three BW 125 kHz, 250 kHz, & 500 kHz with spreading factors from 7 to 12 and transmission power of 2dBm, 5dBm, 8dBm, 11dBm, and 14dBm. The calculation of the link budget is carried out in five cases by varying the transmission power from 2 dBm to 14 dBm. In the first case, the link budget is calculated with a tx power of 2 dBm, SF 7-12, and BW 125kHz, 250 kHz, and 500 kHz.

Figure 4.20 illustrates the graph of the link budget at 2 dBm, where the X-axis denotes the SF and Y-axis denotes the link budget (2dBm). The graph concludes that the link budget is highest (-120 dBm) at the SF 7and BW 3 and lowest (-141 dBm) at the SF 12 and BW1.

In the second case, the link budget is calculated with a tx power of 5 dBm, SF7-12 and BW 125kHz, 250 kHz, and 500 kHz

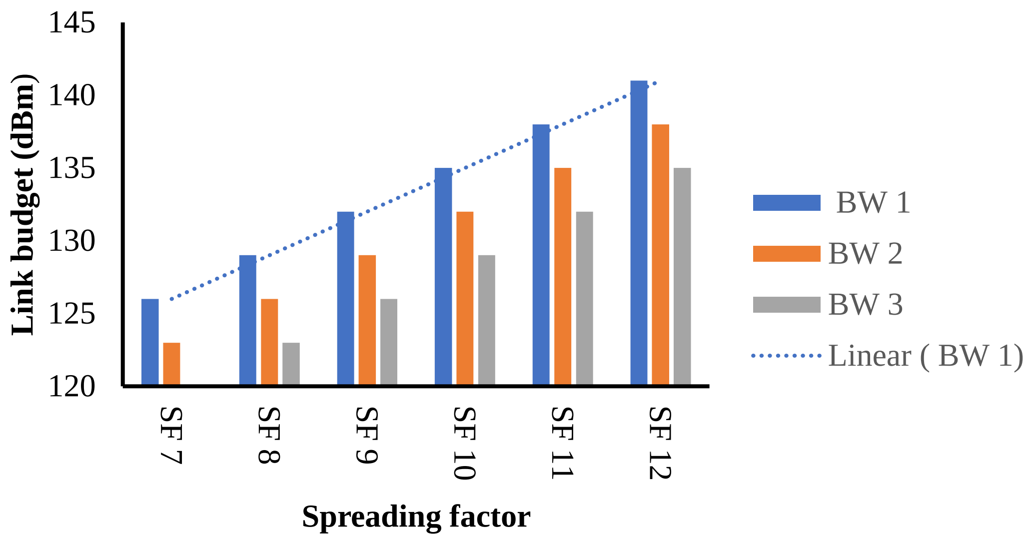

Figure 4.20 Link Budget at 2dBm

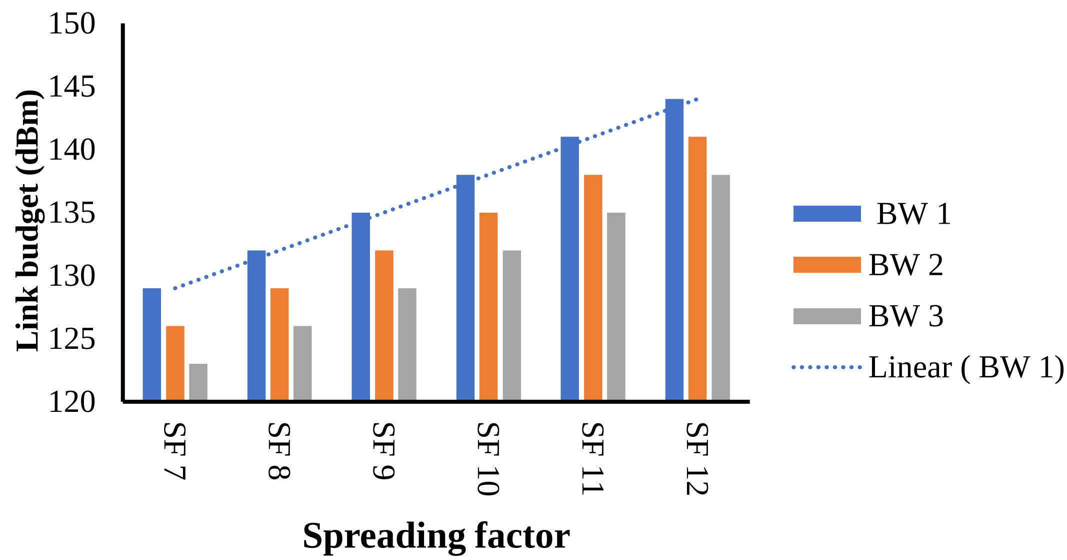

Figure 4.21 Link Budget at 5dBm

Figure 4.21 illustrates the graph of the link budget at 5 dBm, where the X-axis denotes the SF and Y-axis denotes the link budget (5dBm). The graph concludes that the link budget is highest (-123 dBm) at the spreading factor 7, and BW 3 and lowest (-144 dBm) at the SF 12 and BW1.

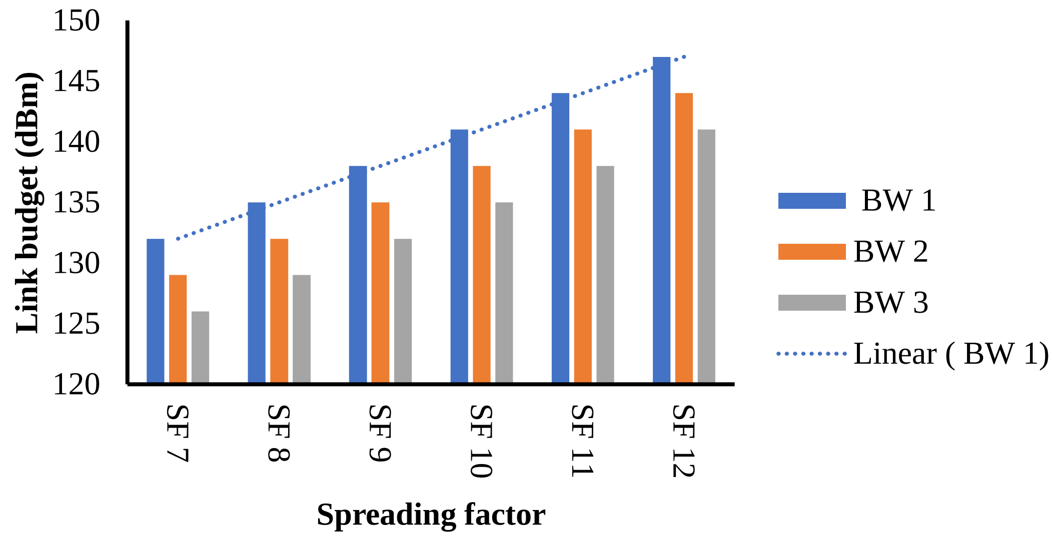

Figure 4.22 Link Budget at 8dBm

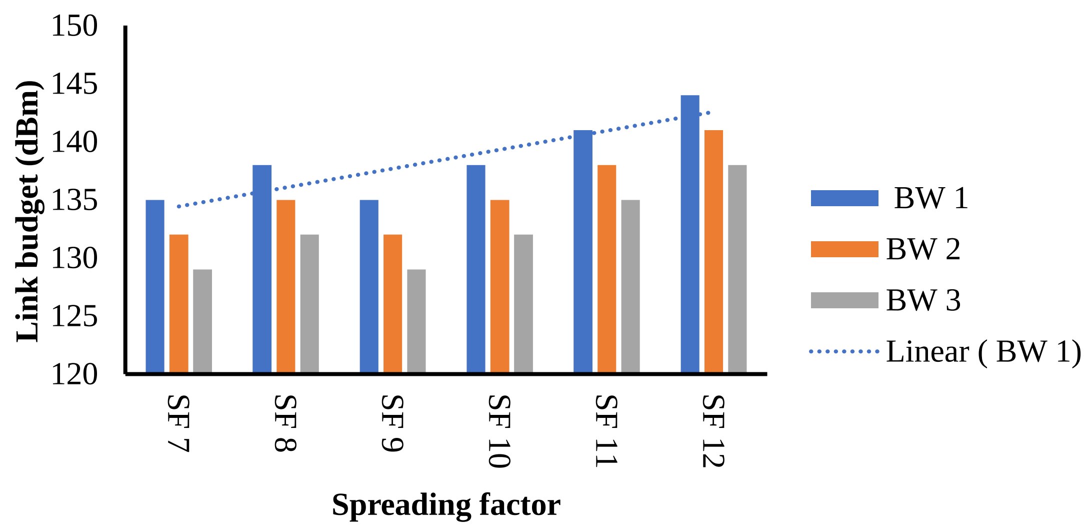

Figure 4.23 Link Budget at 11dBm

In the third case, the link budget is calculated with a tx power of 8 dBm, SF 7-12, and BW 125kHz, 250 kHz, and 500 kHz. Figure 4.22 illustrates the graph of the link budget at

8 dBm, where the X-axis denotes SF and Y-axis denotes the link budget (5dBm). The graph concludes that the link budget is highest (-126 dBm) at the SF 7, and BW 3 and lowest (-147 dBm) at the SF12 and BW1.

In the fourth case, the link budget is calculated with a tx power of 11 dBm, SF 7-12, and BW 125kHz, 250 kHz, and 500 kHz. Figure 4.23 illustrates the graph of the link budget at 11 dBm, where the X-axis denotes SF and Y-axis denotes the link budget (5dBm). The graph concludes that the link budget is highest (-129 dBm) at the SF 7, and BW 3 and lowest (-150 dBm) at the SF12 and BW1.

In the fifth case, the link budget is calculated with a tx of 14 dBm, SF 7-12 and BW 125kHz, 250 kHz, and 500 kHz. Figure 4.24 illustrates the graph of the link budget at 5 dBm, where the X-axis denotes SF and Y-axis denotes the link budget (5dBm).

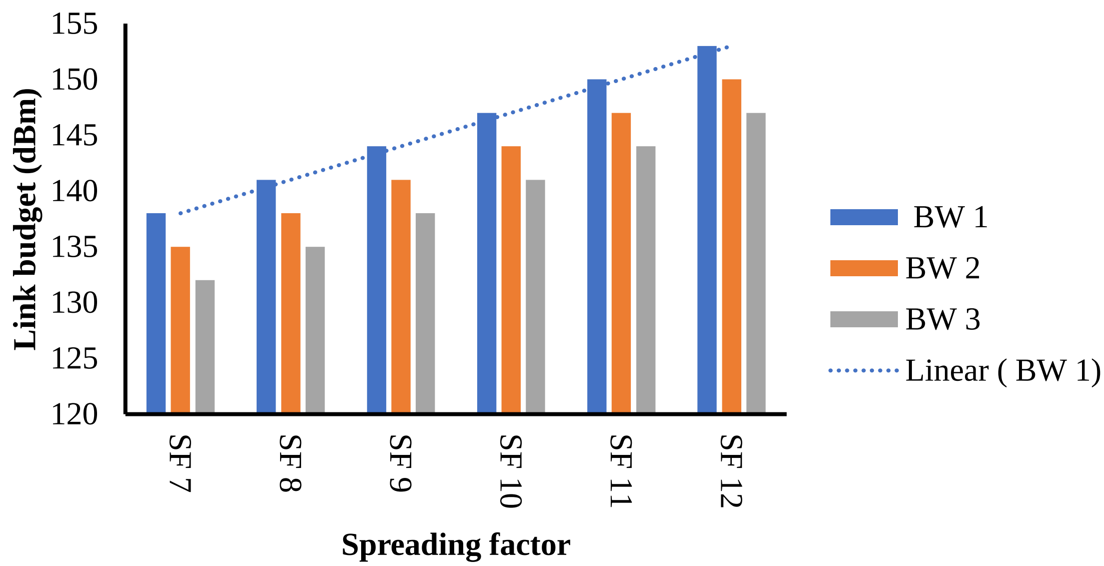

Figure 4.24 Link budget at 14dBm

The graph concludes that the link budget is highest (-129 dBm) at the SF 7, and BW 3 and lowest (-153 dBm) at the SF12 and BW1. From all five cases, it is concluded that the increase in the SF causes decreases in the link budget. The link budget recorded a maximum of 500 kHz of SF7 at 2 dBm. The link budget attained a minimum of 125 kHz of SF 12 at 14 dBm. It is concluded that high Tx power and low BW achieve the low link budget.

4.3.5 Battery Life of Sensor Node

The sensor node's battery life needs to be calculated as part of the analysis, where it determines the optimal parameters that help to increase the battery life. The processing power of 15 mW for 5 ms during sensing value and power usage of 10 W during sleep is considered. During transmission, SF 7, BW 125 kHz, and 2 dB tx power is being considered. The evaluation of the battery life of the sensor node is carried out in three different cases based on payload. In this study, the amount of the data during transmission is low i.e., bytes. A payload of 22 bytes, 25 bytes, and 28 bytes are considered for measuring battery life at different periodicities. Periodicity is measured in minutes, 15 minutes, 30 minutes, 45 minutes, and 60 minutes for transmitting the data. 260 mAh, 1000 mAh, and 2000 mAh Li-ion batteries are three separate battery capacities considered for measuring the battery life of the sensor node in terms of the number of months.

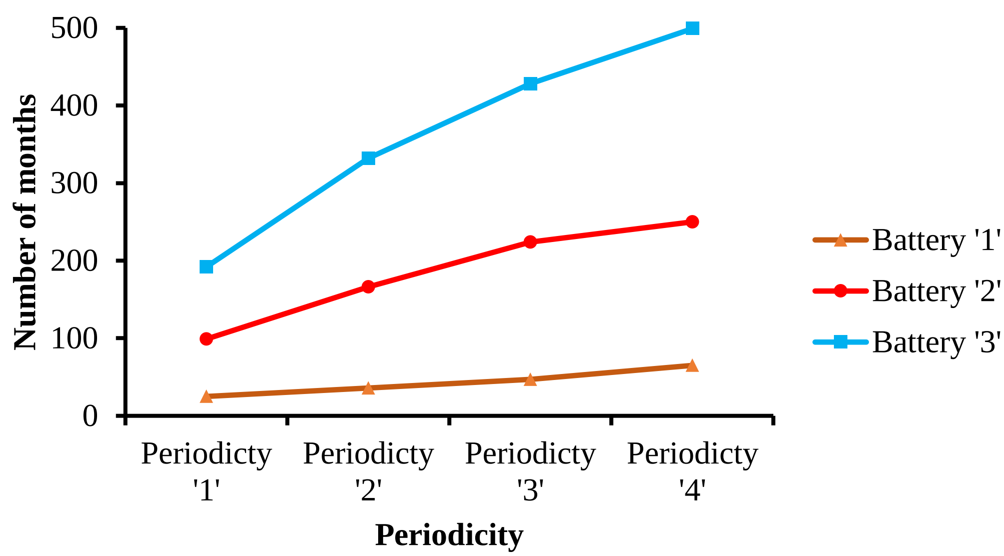

Figure 4.25 Battery Life analysis of sensor node with different periodicities and batteries at 22 Bytes Payload

In the first case, the payload is 22 bytes, the periodicity (15 minutes to 60 minutes), and Li-ion battery capacity of 260 mAh, 1000 mAh, and 2000 mAh. Figure 4.25 illustrates the graph of the first case, where the X-axis denotes periodicity and Y-axis denotes battery life in months. The graph concludes that the battery life is maximum when the periodicity of sending sensor data is 60 minutes. On other hand, the 2000 mAh battery is having the highest battery life at periodicity 4.

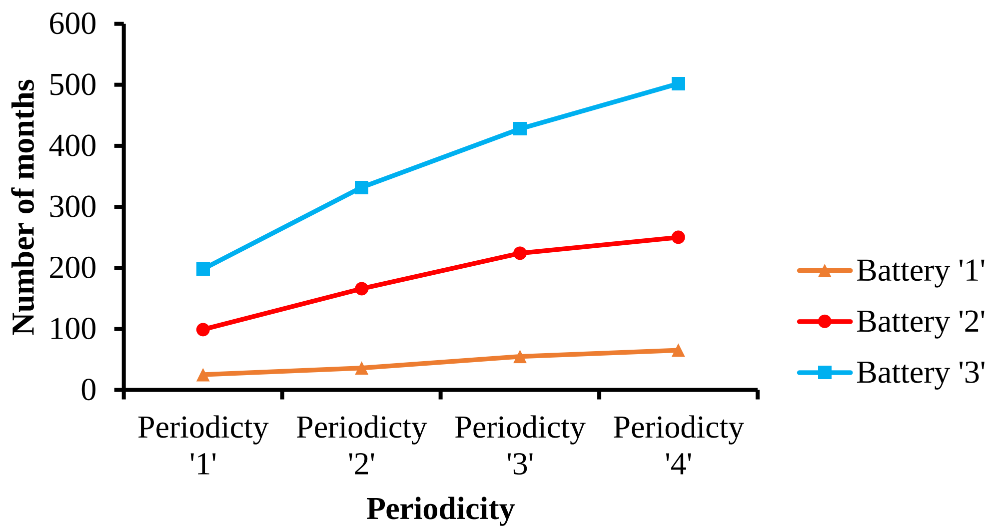

Figure 4.26 Battery Life analysis of sensor node with different periodicities and batteries at 25 Bytes Payload

In the second case, the payload is 25 bytes, the periodicity (15 minutes to 60 minutes), and Li-ion battery capacity of 260 mAh, 1000 mAh, and 2000 mAh. Figure 4.26 illustrates the graph of the second case. The graph concludes that the battery life is minimum when the periodicity of sending sensor data is 15 minutes (periodicity 1). On other hand, the 260 mAh battery is having the lowest battery life at periodicity 1.

In the third case, the payload is 28 bytes, the periodicity (15 minutes to 60 minutes), and Li-ion battery capacity of 260 mAh, 1000 mAh, and 2000 mAh. Figure 4.26 illustrates the graph of the third case. The graph concludes that the battery life is maximum if the periodicity of sending sensor data is 45 minutes (periodicity 3), and 60 minutes (periodicity 4). On other hand, the 260 mAh, 1000 mAh battery is having the same battery life after periodicity 3.

From all three cases, if the sensor's periodicity of sending data is 15 minutes, then the battery life is minimal. It is also observed that the battery life is the same for the i) 260 mAh and 1000 mAh at payloads of 22 bytes and 25 bytes, respectively ii) 1000 mAh with payloads of 22 and 25 bytes.

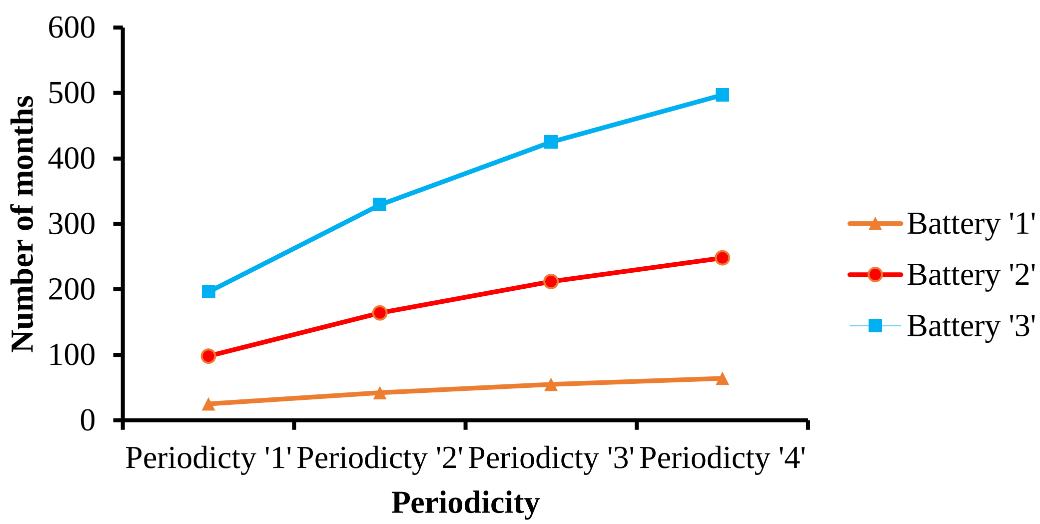

Figure 4.27 Battery Life analysis of sensor node with different periodicities and batteries at 28 Bytes Payload

4.4 Chapter Summary

This chapter addresses the significance of performing the analysis of the LoRa network for choosing the optimal parameters that are required for implementing the system based on LoRa. The energy consumption of nodes is evaluated by varying parameters like transmission power, number of nodes, number of gateways, SF, and BW for the CF of 433

MHz with FLoRa simulation. The bit rate, ToA, receiver sensitivity, link budget, and batter life of sensor node are evaluated by varying parameters like CR, payload size, BW, and Tx power. From the analysis, it is concluded that the SF7, 125kHz BW, and 2 dBm Tx power are the optimal parameters that are preferred for the system implementation. The performance analysis of LoRa network is performed and finalized the optimal parameters for effective and reliable real-time implementation of customized hardware with LoRa network to obtain sensor data from the bins.

A research article is published about the performance analysis of LoRa network and the **publication** is: Shaik Vaseem Akram, Rajesh Singh, Mohammed A. AlZain, Anita Gehlot, Mamoon Rashid, Osama S. Faragallah, Walid El-Shafai, Deepak Prashar, "Performance Analysis of IoT and Long-Range Radio-Based Sensor Node and Gateway Architecture for Solid Waste Management is published in Sensors, MDPI (SCI).

Chapter 5
Development of Cloud Server

In this chapter, the development of the cloud server for waste management application is discussed. The significance of the integrating cloud server with the customized gateway and sensor node is described. The customized gateway and sensor node is interconnected with the blynk server and Thingspeak server through Wi-Fi and the API) is discussed in detail. The development of the customized cloud server based on Mongo database, Node.js, and Angular framework is demonstrated.

5.1 Cloud Server

The technological advancement of wireless communication enables to implementation of an intelligent system for monitoring, visualizing real-time data through internet connectivity. The implementation of IoT-enabled sensors nodes is producing a large amount of sensor data on the cloud. The volume of data collected is huge and processing such data locally is impractical. It is challenging for the local server to obtain, store and process the enormous quantity of data created by the IoT-enabled sensors. A cloud is denoted as an element of application service or software (Ray, 2016). Real-time data, data visualization, data capture, API protocol, and cloud model type are the most important criteria for designing cloud systems. There are three types of services provided by cloud infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS) (Namasudra, 2018). Network, hardware, and other services are handled by the IaaS provider. SaaS supports everything, while PaaS supports the operating system (OS) and application platform. It is a cloud service model based on Infrastructure as a Service (IaaS).

A cloud server is an open logical server that constructs, hosts, and distributes cloud computing services over the Internet. A cloud server is a virtual infrastructure that hosts applications and data processing. A cloud server is a computer that is built, hosted, and distributed through the internet and can be accessed from anywhere. Cloud servers are built with the help of virtualization software to categorize the physical server into multiple virtual servers. Data storing and sharing, web hosting, and software or application are some of the features of the cloud server. A cloud server is interfaced with the hardware for obtaining and monitoring the sensor data and visualizing it on the graphical user interface (GUI). The server is deployed into different three kinds of clouds namely public cloud, private cloud, and hybrid cloud. Public cloud is a traditional model that requires minimal technical for utilizing because there is no effort required for deployment, maintenance, and customization of infrastructure. e.g., The technologies that are implemented in daily life like smartphones and laptops. The private cloud is used by business organizations for managing their activities and access to the authorized user only. A hybrid cloud is an integration of both public and private clouds. For different functions, an organization can employ a public and private cloud simultaneously, for obtaining the ease of use and other benefits of a public cloud while preserving a private cloud as needed. An IoT-cloud architecture is intended to coordinate cloud-IoT services by establishing the device's intent for empowering communication amongst interconnected devices in a cloud-scale environment.

The cloud server is integrated with IoT-enabled hardware through different IoT protocols. This protocol enables the hardware to connect to the internet from any location. MQTT, Hypertext transfer protocol (HTTP), and Constrained Application Protocol (CoAP) are three basic protocols having the capability of connecting, controlling, and monitoring the IoT-enabled hardware devices. MQTT is a lightweight publication and subscription-type message protocol specifically built for battery-powered devices. The subscriber, publisher, and broker models are used in MQTT. The publisher's role in the model is to acquire data and transmit it to subscribers via the intermediary layer, which is the broker. The broker’s responsibility is to assure security by double-checking publisher and subscriber authorization. Low energy consumption, low processing, and memory resources, low bandwidth, reliability, and working over wireless networks are the features of MQTT. HTTP is a collaborative, decentralized, hypermedia information system application protocol, based on the Transmission Control Protocol (TCP)/IP communication protocol. It permits users to transmit data across the Internet. HTTP is a request-response protocol that allows users to interact with web resources such as HTML files by sending hypertext messages between clients and servers. HTTP clients commonly uses TCP connections to communicate with servers. CoAP is a specialized web transfer protocol employed for constrained nodes and constrained networks in IoT. CoAP is a protocol that allows basic, restricted devices to connect to the Internet of Things, even across constrained networks with poor bandwidth and availability. CoAP serves as a type of HTTP for restricted devices, allowing sensors and actuators to communicate across the internet of things. Due to its low power consumption and low network overhead, the protocol is designed for reliability in low bandwidth and high congestion situations.

A wide range of IoT-cloud servers is used for logging the sensor data of the hardware device through the internet. Blynk SAP, Cayenne, Amazon Web Services (AWS), IBM's Watson, Microsoft Azure Thing Worx IoT Platform, Salesforce IoT Cloud, Cisco IoT Cloud Connect, GE Predix, Oracle Integrated Cloud, Firebase (Google), Parse (Facebook), Thingspeak, IMPACT (Nokia) and Mind Sphere (Siemens) are the few IoT-cloud platforms(Emeakaroha et al., 2015; Tamas Pflanzner & Kertész, 2016; Tamás Pflanzner & Kertész, 2018). Among these Thingspeak, blynk cloud, and Cayenne are the frequently used open-source cloud servers for interfacing the hardware based on Arduino Uno board, Raspberry Pi, and ARM. Thingspeak, blynk cloud, and Cayenne comprise of API that assists to initiate communication between the server and hardware device.

5.2 Customized Cloud Server

The customized hardware for the waste management system is designed and developed for monitoring and logging the sensory data of the bins in chapter 3. Sensor node and gateway are the customized hardware that is realized for the waste management system. The sensor node is based on the ATMega328P microcontroller and SX 1278 LoRa module. The gateway is based on the ATMega328P microcontroller, SX1278 LoRa module, and

ESP8266 Wi-Fi module. The optimal network parameters that realized through performance analysis and embedded in the gateway and sensor node like Spreading factor7, 125 kHz (BW), code rate 4. After the completion of the programming, to evaluate the performance of the sensor node and gateway, the sensor nodes are embedded in the four different bins as shown in figure 5.1.

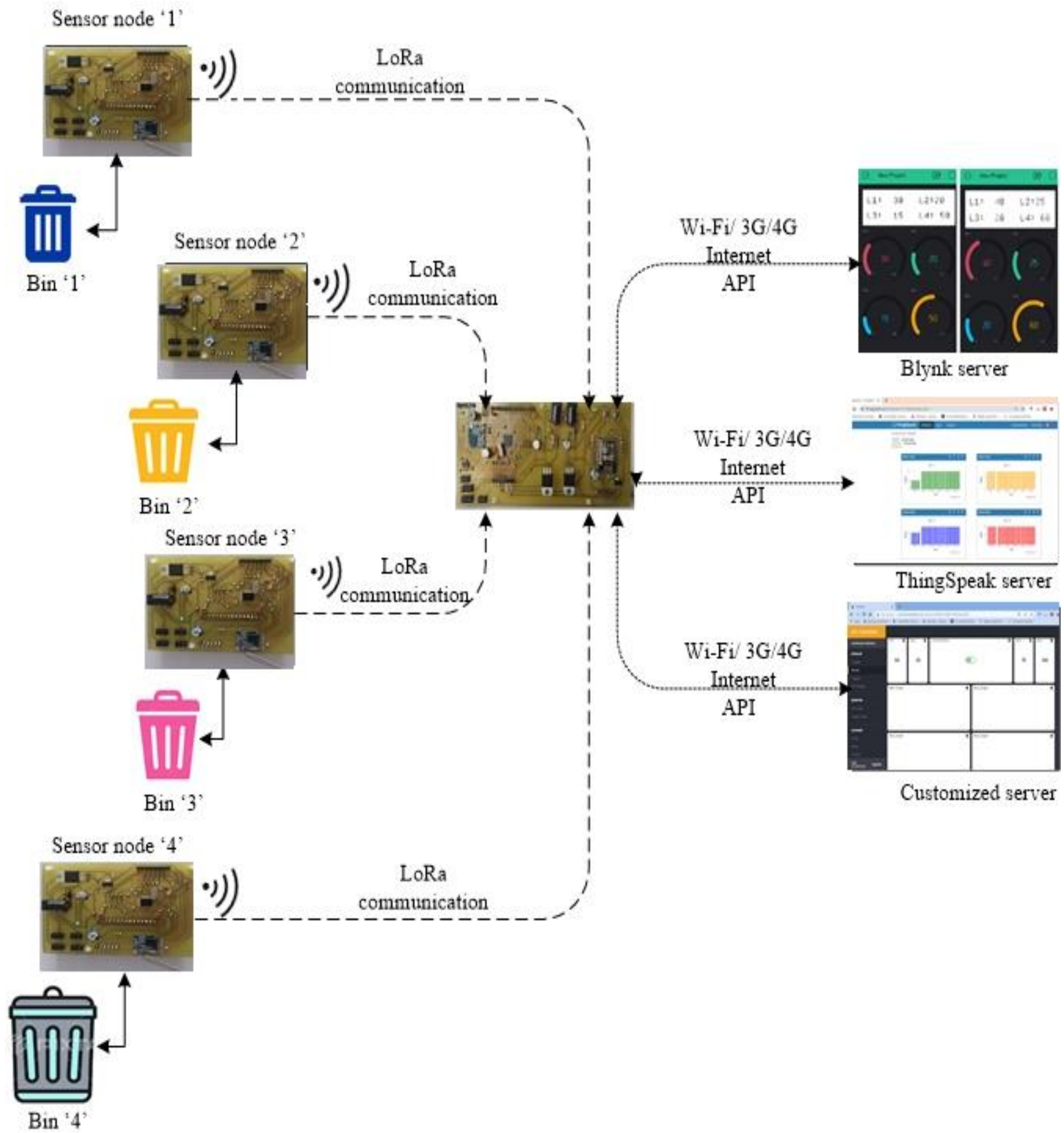

Figure 5.1 Architecture of Interfacing Customized Hardware with Cloud Server

During programming, the four-sensor node is assigned a unique ID, allowing the gateway to easily detect and route data to the cloud server with ID. To log the level and quantity of waste filled in the bins, each sensor node is connected to an ultrasonic sensor and a load cell sensor. The sensory data is transmitted to the gateway by the sensor node using LoRa connectivity. The placement of gateway is positioned at a location with availability of internet connectivity. The internet connectivity to the gateway is provided through Wi-Fi. The gateway interconnects the sensor node to the cloud server with an API through the internet. The interconnection of the cloud server and sensor node is established by embedding the API of the cloud server into the gateway.

5.3 Blynk

Blynk app enables to connect, visualize and control the hardware-based application remotely when connected to it through the internet. It is a platform to implement a smartphone-based application with a wide range of microcontrollers like Arduino Uno, ESP 8266 Wi-Fi, and Raspberry Pi. Blynk platform is the integration of three main components Blynk App, Blynk server, and Blynk libraries. Blynk app assists to build the graphical based interface with distinct widgets available in it. Blynk server allows establishing communication between hardware and software. It has the feature to create and run its private Blynk server locally. Blynk Libraries consist of all the libraries related to the hardware platform for enabling communication with the server and route all the outcoming and incoming commands.

The working mechanism of the Blynk platform with system hardware is shown in figure 5.2, here every time you press a button on the Blynk app dashboard, the message is routed to the Blynk Cloud, where it is delivered to your hardware through internet connectivity. Similarly, the device sent the data to the Blynk cloud server through the internet, and it can be visualized on the dashboard of the blynk app. The connection to the Blynk cloud is possible with the assistance of wireless communication like Bluetooth, Wi-Fi, USB (Serial), and BLE, Ethernet, and GSM. Direct pin manipulation with no programming, feasibility of virtual pins integrating new functionality is the features of Blynk.

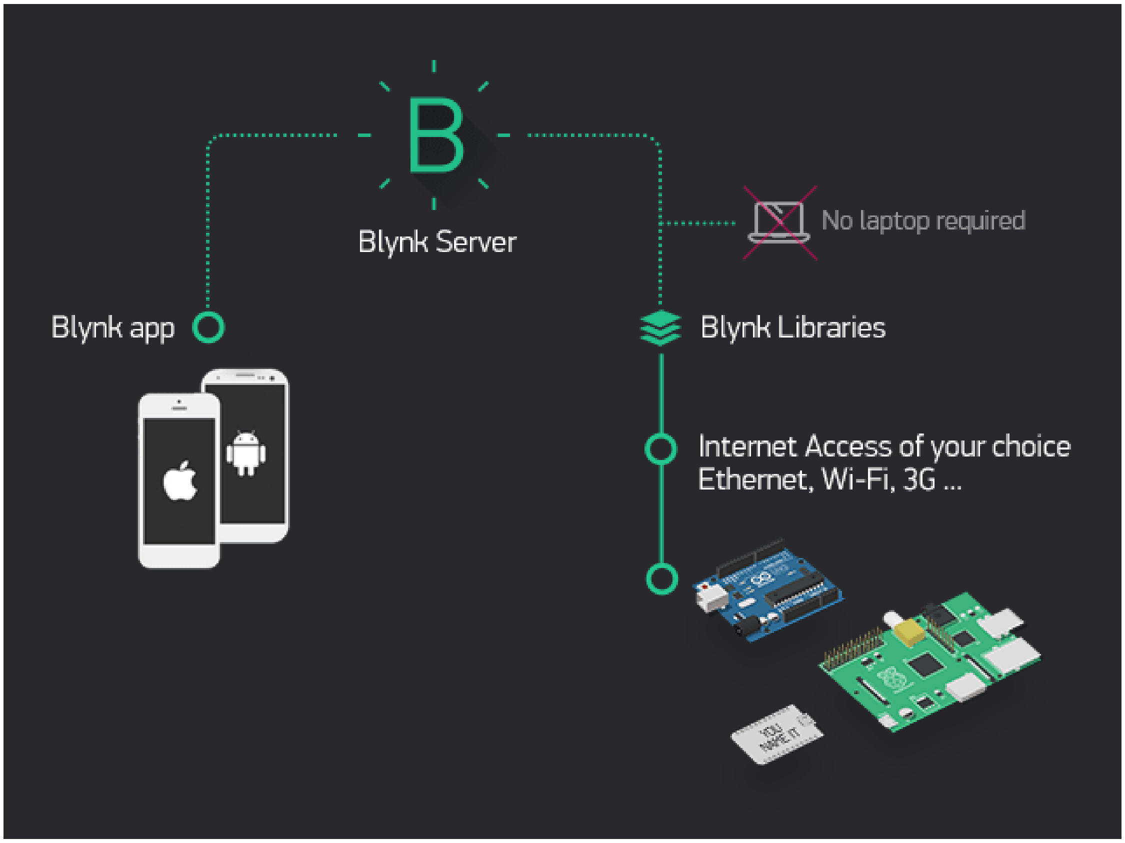

Figure 5.2 Working of Blynk Platform

5.3.1 Blynk Interfacing with Customized Hardware

From the above section, it is clear that the Blynk can connect to the various microcontrollers and distinct boards, built with internet capability. The customized gateway is connected to the LoRa, and ESP 8266 can connect to the Blynk platform through the internet. The first step is to create an account with the Blynk app. Figure 5.3 shows the interface of creating an account with specified credentials processed by clicking on the "create new account". After entering the specified credentials, a new account is created, where the dashboard of creating a new project appears as shown in figure 5.3. The new project is created after inserting the name of the project and selecting the specific hardware board. In this case, the ESP 8266 board is selected as the device because it is used in the developed system. The project is created as the necessary details like project name and board name are provided in the columns of the dashboard.

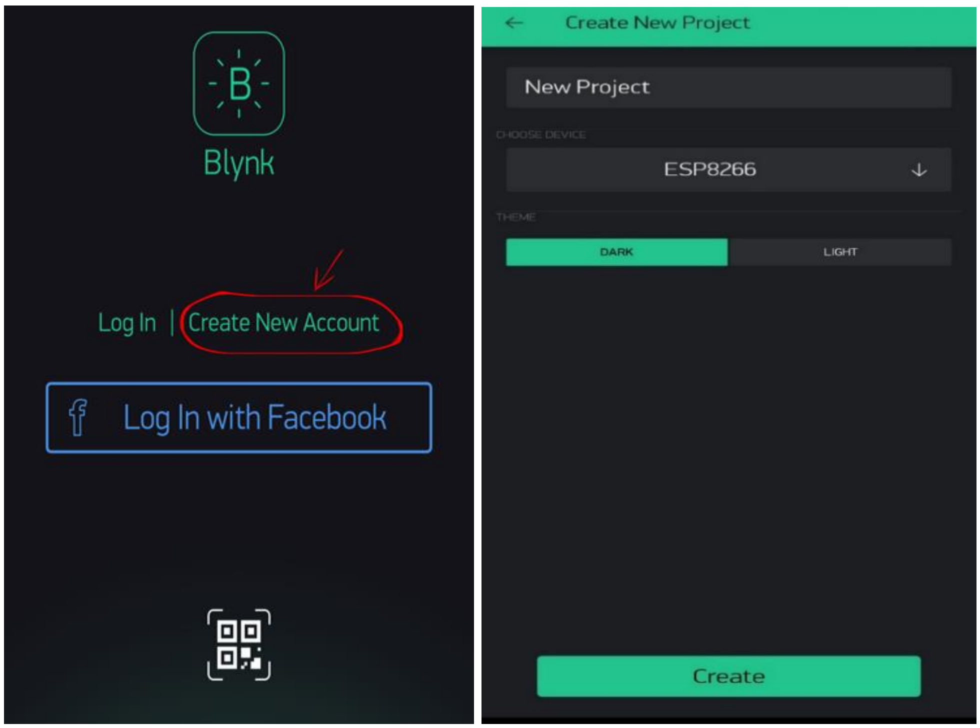

Figure 5.3 Interface of Creating an Account and a Project

On the creation of a new project, an auth token generated by Blynk allows to connect the app through ESP 8266 gateway as shown in figure 5.4. and it is sent to the respective mail, provided during creating the new account. The received Auth token in the email is placed in the program of the gateway. Now the gateway is interfaced with the blynk app and Auth token is different for each project. The dashboard of the new project is shown in figure 5.4. A new widget is created by clicking on the plus sign, available on the top right of the dashboard. Depending upon the type of system and application, the widgets are selected. Every widget has a specific feature to visualize the hardware data in the graphical user interface. The gauge widget is selected for visualizing the sensor data of the level measurement sensor in terms of the % format. To visualize the sensor data of the four different bins, four widgets are created in the new project dashboard shown in figure 5.5. Bin '1', Bin '2', Bin '3' & Bin '4' are the name that is represented for the bins in the Blynk application.

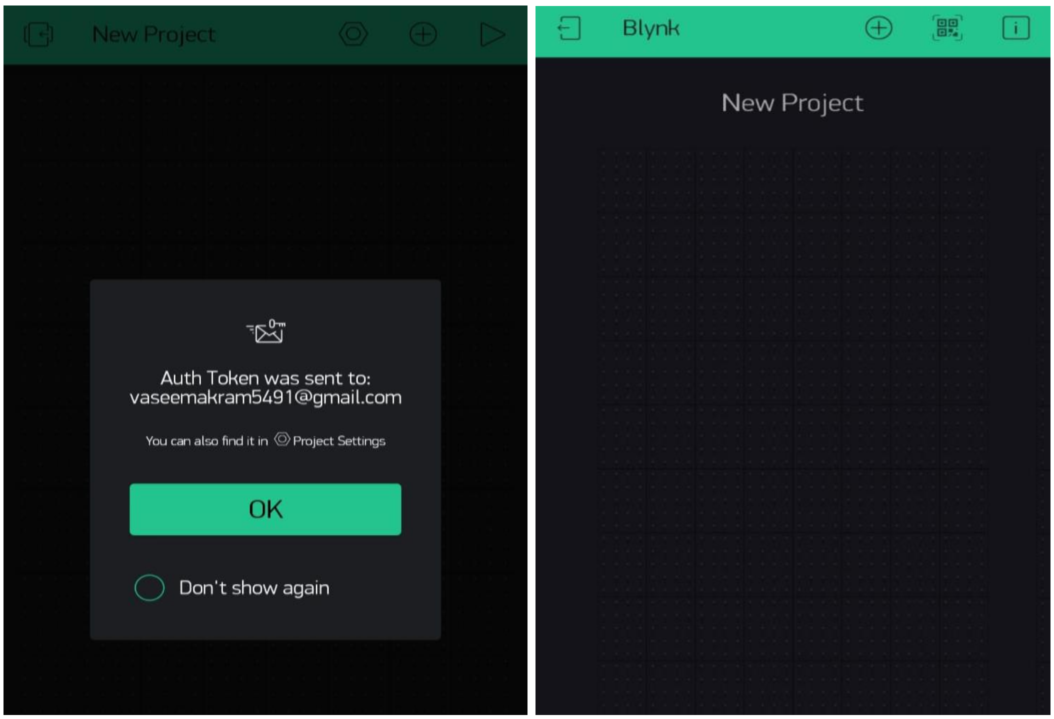

Figure 5.4 Dashboard of New project with Authorized Token

Now the hardware is interfaced with Blynk, and the sensory data can be observed on the dashboard. Two different scenarios have been created to test the gateway is logging the status of the bins. In the first scenario, the level of the four bins are visualized as Bin '1' (30%), Bin '2' (20%), Bin '3' (15%), and Bin '4' (50%). These are the status of the four bins received from the four-sensor node. In the second scenario, the level of waste in the four bins has increased to a certain amount. Here the level status of the four bins are recorded as Bin '1' (40%), Bin '2' (25%), Bin '3' (20%), and Bib '4' (60%). Any change in the waste level in the bins will be simultaneously updated in the Blynk through the gateway and Blynk server. A display unit is also visualized in the dashboard, where the status of the bins is represented as L1 (Bin '1'), L2(Bin '2'), L3 (Bin '3'), and L4 (Bin '4').

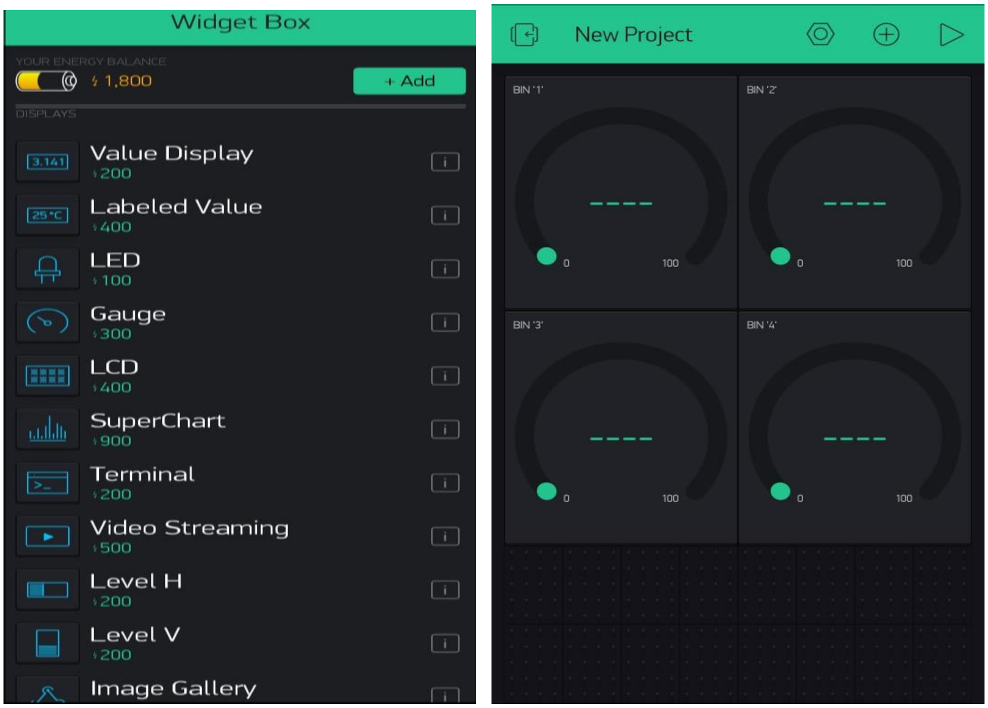

Figure 5.5 Widget Box and Dashboard with Four Widgets

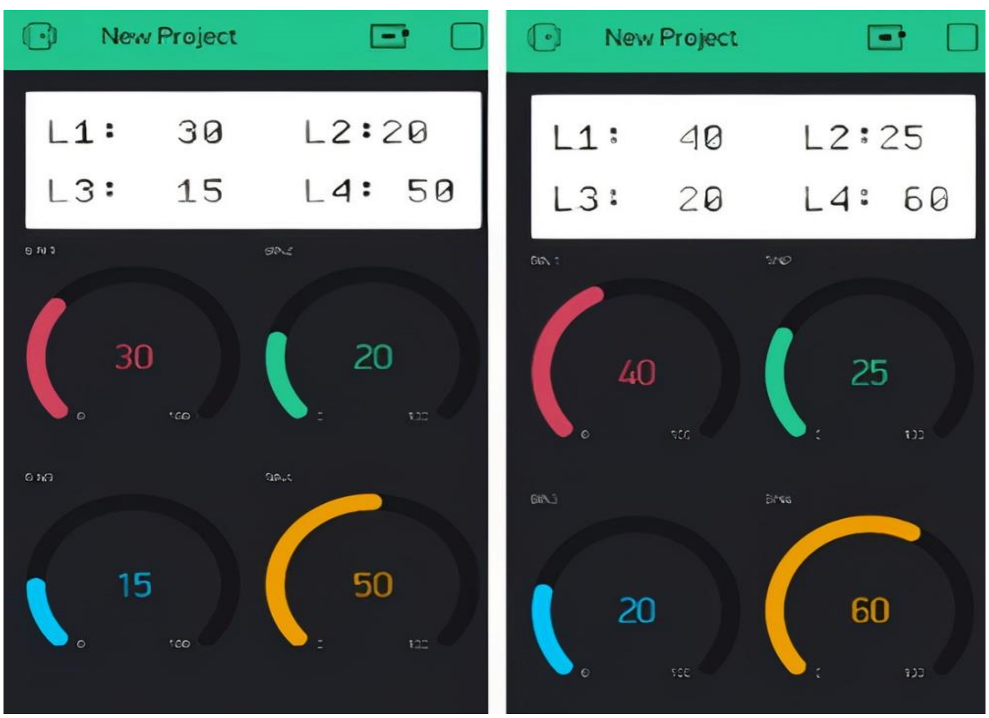

Figure 5.6 Status of the Four Bins in Blynk Dashboard

5.4 Thingspeak Server

Thingspeak is an application platform for IoT system development. It assists to design an application that displays data acquired by sensors. It allows to integrate the sensor data along with a wide range of systems, third-party platforms, and technologies, including popular IoT platforms like Arduino and ioBridge. Thingspeak has channels and each channel includes eight fields, three location fields, and one status, which can display data. After building a Thingspeak channel, one can publish data to the channel, process the data, and retrieve the data using an application. To support IoT systems, the Thingspeak platform has features: collect, analyze and act. Collect denotes a collection of data from the sensor and sending it to the cloud. Analyze means Thingspeak can evaluate data obtained from sensors and create a virtual representation of the information. Thingspeak server supports the various processing platforms including Arduino, ESP8266 Wi-Fi Module, Particle Photon and Electron, Raspberry Pi, LoRaWAN, Senet, Things Network, Libeliu, and Beckhoff. Obtain data in private channels, distribute data with public channels, RESTful and MQTT APIs, Event scheduling, MATLAB® analytics, and visualizations and are the features of the Thingspeak server. The interfacing of the internet-based hardware platform with the Thingspeak server is established through the API key. This key is a unique identification for authenticating the user with API for checking the status on the server.

Thingspeak server consists of two different API keys namely: Read API key and Write API key. Write API key permits to the write the data in the channel and this key is embedded in the programming of the hardware that is implemented. The customized gateway is embedded with the Write API key, to call the sensor values of the bins through the gateway based on ESP 8266 Wi-Fi module. Read API key is an additional key that allows the other individuals to read the data of the channel. Thingspeak server comprises of two APIs including REST API and MQTT API, which allows to update, clear the channel. REST (representational state transfer) is an architectural method which uses HTTP to communicate and is built on a request-response architecture. Thingspeak employs the REST API functions GET, POST, PUT, and DELETE to create and delete channels, read and write channel data, and clear the contents in a channel. The server receives a request from a web browser or client, and the server responds with data in the requested format. MQTT is a publish/subscribe messaging system which communicates through TCP/IP connections or WebSockets. MQTT over WebSockets is more secured with SSL. To publish or subscribe to a channel's update, a client device must be connected to the MQTT broker.

5.4.1 ThingSpeak Server Interfacing with Hardware

In this section, the interfacing of the ThingSpeak server with customized hardware is discussed. The ESP 8266 Wi-Fi module embedded in the gateway encourages to connect the complete hardware including the sensor node to the ThingSpeak server. To operate the ThingSpeak server, creating a new account is mandatory with necessary credentials details. After providing the necessary details for creating a new account, a new account is built for logging and visualizing the sensor data in the channel. Figure 5.7 illustrates the GUI of creating a channel in the ThingSpeak server, consisting of different columns where the necessary information such as ‘Channel name’, number of the field label. The function of the channel is to store the sensor data and it consists of customized field labels, customized as per requirement. Four field labels are selected to connect the four sensor nodes to the ThingSpeak server. The channel is created with the four field channels, denoted as Bin ‘1’, Bin ‘2’, Bin ‘3’, and Bin ‘4’. The creation of the channel is completed with four field labels and further the Write API key and Read API key need to be generated. In the channel, the API key menu is chosen for generating the API key or already available API key for initiating the communication between the gateway and the ThingSpeak server.

Figure 5.8. illustrates the GUI of the channel, where it allows to create a Write API key and Read API key. The write API key is incorporated in the hardware's programming of the ESP8266 Wi-Fi module of the gateway, enabling it to write into the channel. Read API key is provided for public accessing of the channel to others for reading the data. This Write API key is considered and inserted the Write API key in the ESP 8266 Wi-Fi module

for writing the sensor data of the four bins with a timestamp. Now the sensor node through the ESP8266 Wi-Fi module, gateway writes the sensor data in the channel as shown in figure 5.8.

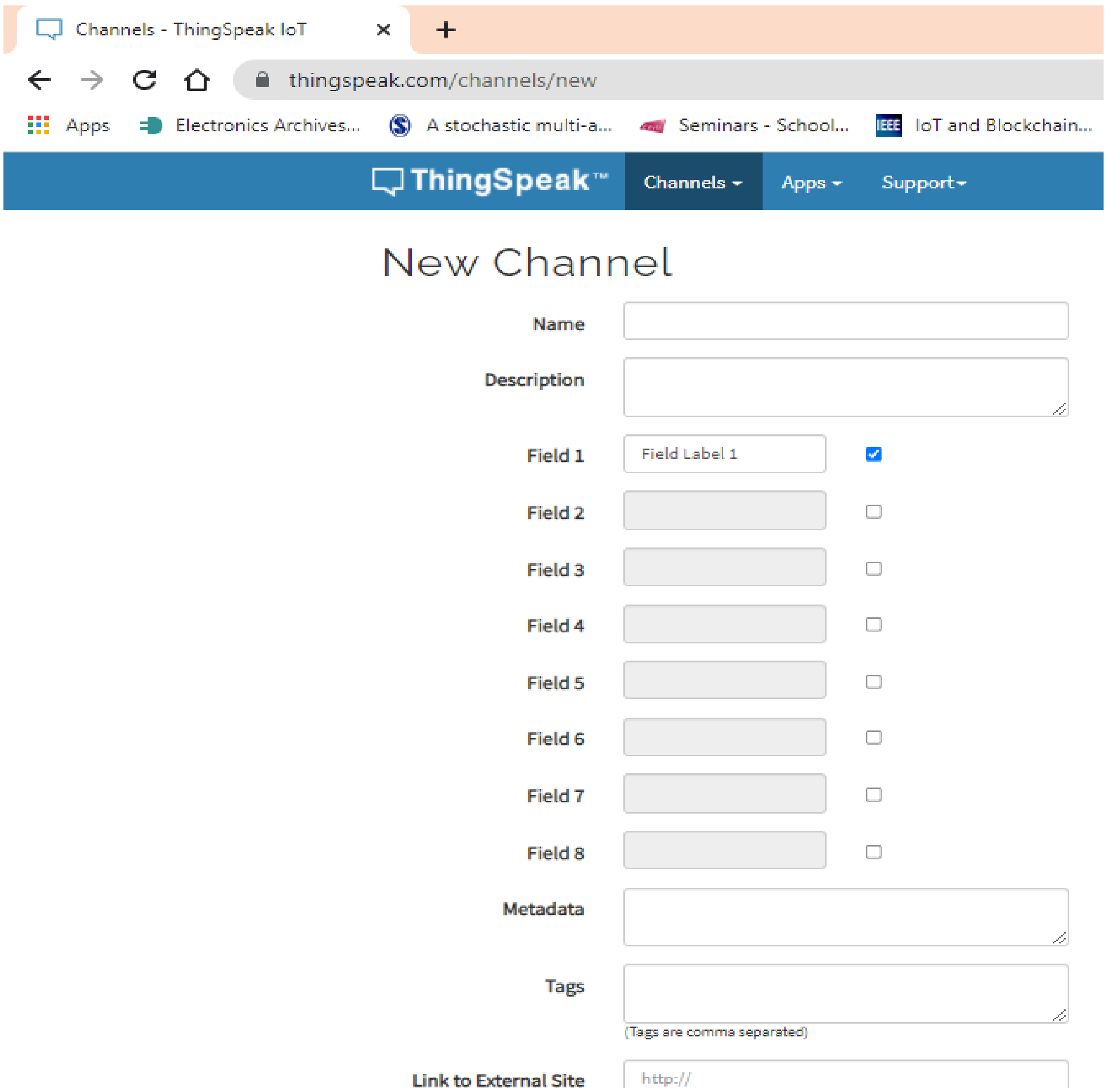

Figure 5.7 Creating a Channel in the ThingSpeak Server

Figure 5.9 illustrates the status of the four bins in graphical representation with four different field labels. Four field labels are represented with the following name Bin ‘1’, Bin ‘2’, Bin ‘3’, and Bin ‘4’. The X-axis of the graph represents the time and the Y-axis of the graph presents the filling status of bins in terms of percentage (0-100%). The four bins are filled with different levels of waste in it.

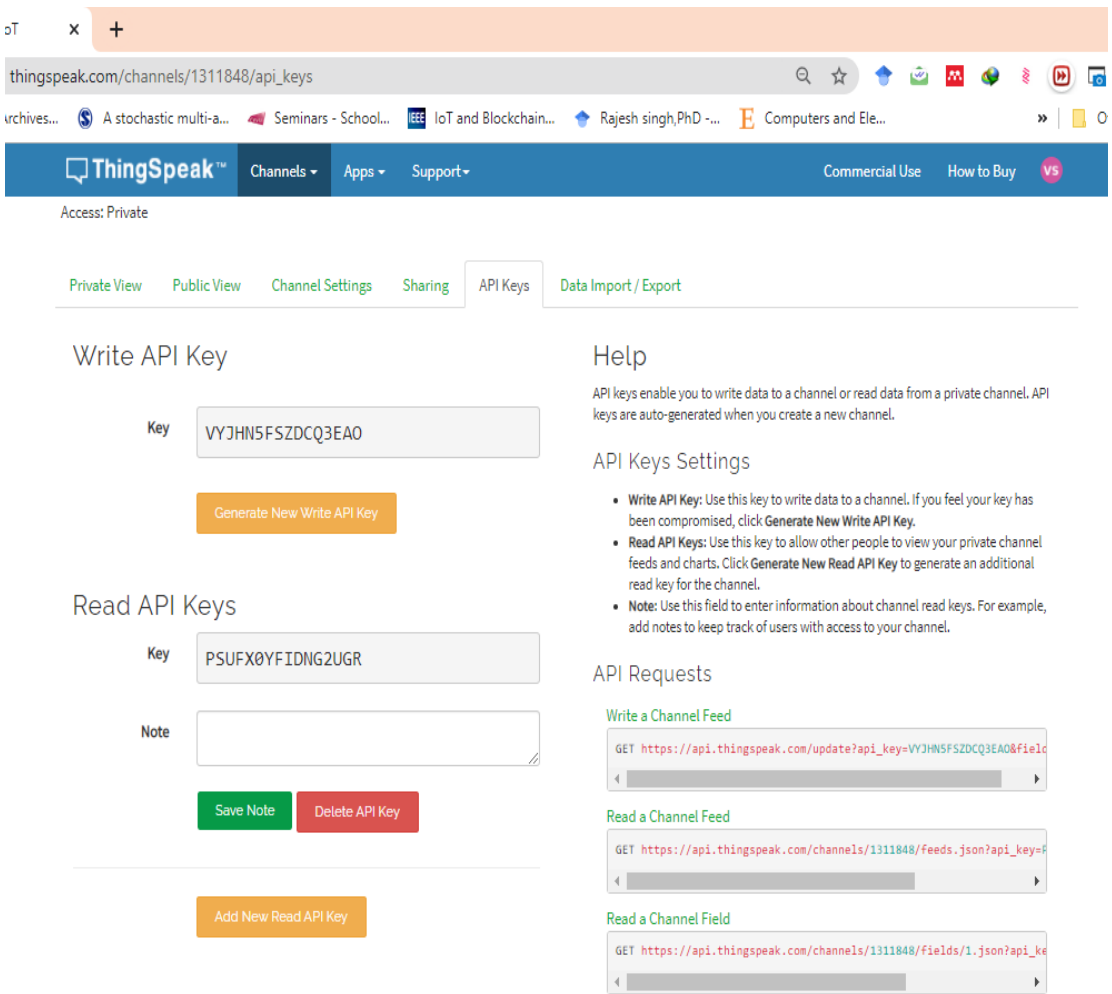

Figure 5.8 Generating Write API Key in the Channel of ThingSpeak Server

The graph shows Bin '1' filing status is 25 % and after the deposition of the waste in bin '1' the level of waste has increased to the 50%. Similarly in the cases of Bin '2', the level of the waste available in Bin '2' is remained constant at 50% as no additional waste is deposited in the bins. Bin '3', the initial level of the waste is 50% and a certain amount of waste is deposited in the bin. Further addition of waste in the bins has increased the level of waste in bin '3' more than 50% and less than 75%. Bin '4', the bin is completed filled with waste and the level of the waste is constant for a certain time as shown in the graph. The realization of customized hardware with the ThingSpeak server is processed with the sensory data of the four bins into the channel of the server.

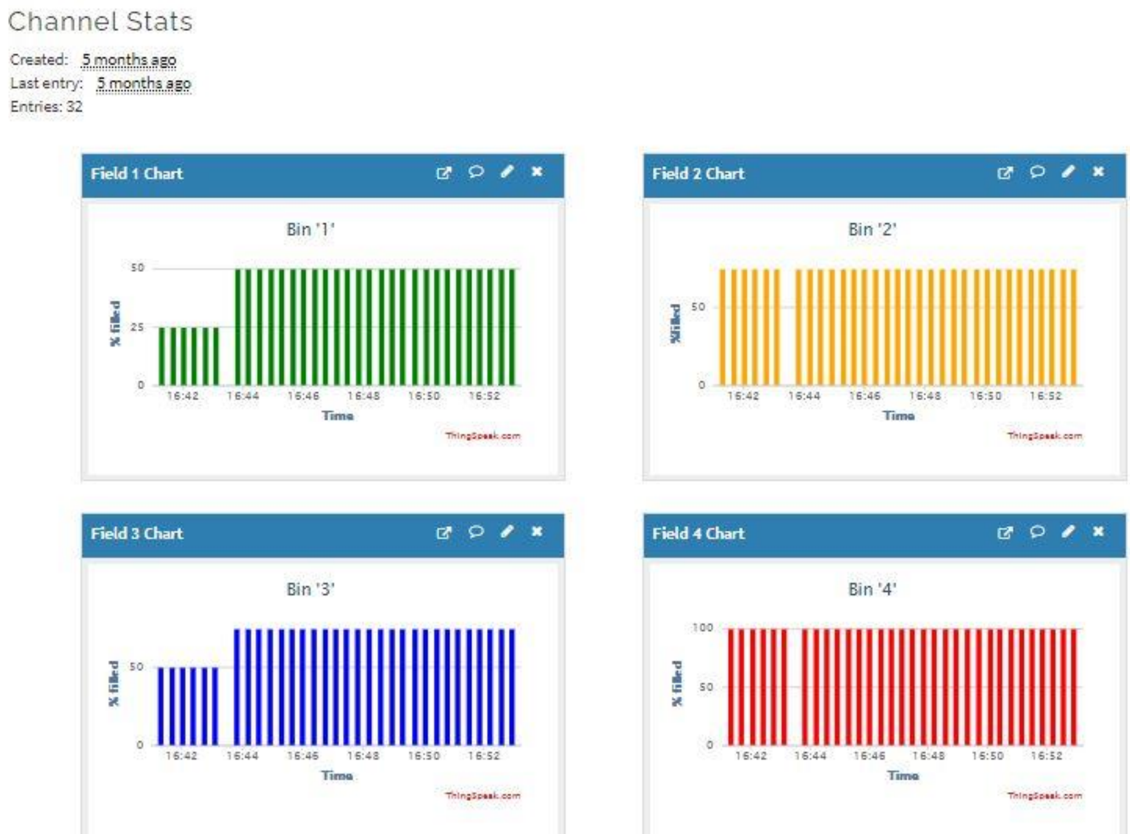

Figure 5.9 Sensor Data of Four Bins Writing in the Channel

5.5 Customized Waste Management Server

The implementation of the customized hardware is done with open cloud platforms like the ThingSpeak server and Blynk. The main aim of the research is to implement a waste-to-money model, by integrating a waste management server with a lightweight blockchain server. To achieve it, a customized waste management server (cloud server) is designed which can process and envision the status of the bins to obtained sensory data. This customized waste management server is specifically dedicated to the customized LoRa and ESP 8266 Wi-Fi-based gateway. The data received from the sensor nodes are directly logged in this server through the gateway. This server is built with limited resources for the waste management application and with full control over the performance functionality including data privacy. Security, customization, and flexibility are the some of significant features of the developed waste management server. 1 GB Random access memory (RAM), 1 core processor, 20 GB Solid-state drive (SSD) is the hardware configuration taken for developing the waste management server. This waste management server is based on Mongo Database and Node.js.

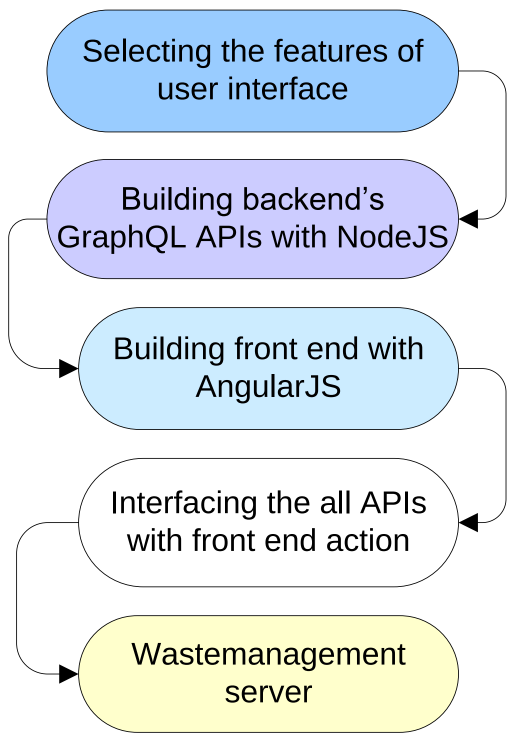

Figure 5.10 Development of Waste Management Server

Figure 5.10 illustrates the flow diagram presents the mechanism followed for creating a waste management server. Initially, the features related to the development of the user interface (UI) are validated. After confirming the features of UI, the next stage is to build the backend. In the backend, the main focus is on the server side where NodeJs is an application runtime environment that lets to create JavaScript-based server-side applications. It's also lightweight and efficient, with the ability to use JavaScript on both the front end and the backend. The frontend is the graphical user interface of a custom cloud server is to visualize the data from the hardware in the graphical user interface. All the APIs of the backend are tested on the postman platform. The front end is developed with the assistance of the AngularJS framework. After the completion of front-end development, all APIs are connected through front-end action.

The custom waste management server is developed as shown in figure 5.11. The waste management server is developed with two different API protocols for data exchange in between backend & front end and backend & customized gateway. The interface between the backend & front end for data exchange is implemented with REST API. REST APIs use HTTP requests to conduct basic database activities within a resource, such as creating, reading, updating, and deleting records. REST APIs should accept JSON for request payload and also send responses to JSON. JSON is the standard for transferring data. The interface between the backend and customized gateway is implemented with the MQTT protocol. MQTT (Message Query Telemetry Transport) is an OASIS standard communications protocol for low-power IoT devices because of its small code footprint and low network bandwidth, it is perfect for connecting faraway devices.

The user interface of the waste management server comprises different features, and they are categorized into three categories develop, monitor, account. Widgets, boards, triggers, and API managers are the components of the developed feature. In the Widgets component, different end points have existed. The end points are determined according to the requirement of application [Like temperature, humidity, level measurement, pH value, etc.]. In the board's component, the visualization of the data and the number of end points are presented. In the trigger component, we can subscribe for generating the alerts of the bins on the mail or mobile application. In the API manager component, we can generate the API keys that are required for interfacing with the customized gateway for logging the sensor data on the server. The API key generated for solid waste management "QCp^H<eXj8h6,%x3".

5.6 Real-time implementation

The customized hardware, selection of optimal parameters, and development of custom waste management server are achieved for system implementation. The real-time implementation is carried out by deploying the customized sensor nodes in the bins. Before the deployment of sensor nodes in the bins, the identified optimal parameters are logged in the sensor node through programming. Additionally, customized features like mapping, symmetric encryption, and demand on transmission are also logged in the sensor node. The threshold value identified by measuring the distance between the ultrasonic sensor and the bottom of the bins is 42cm (figure.5.12).

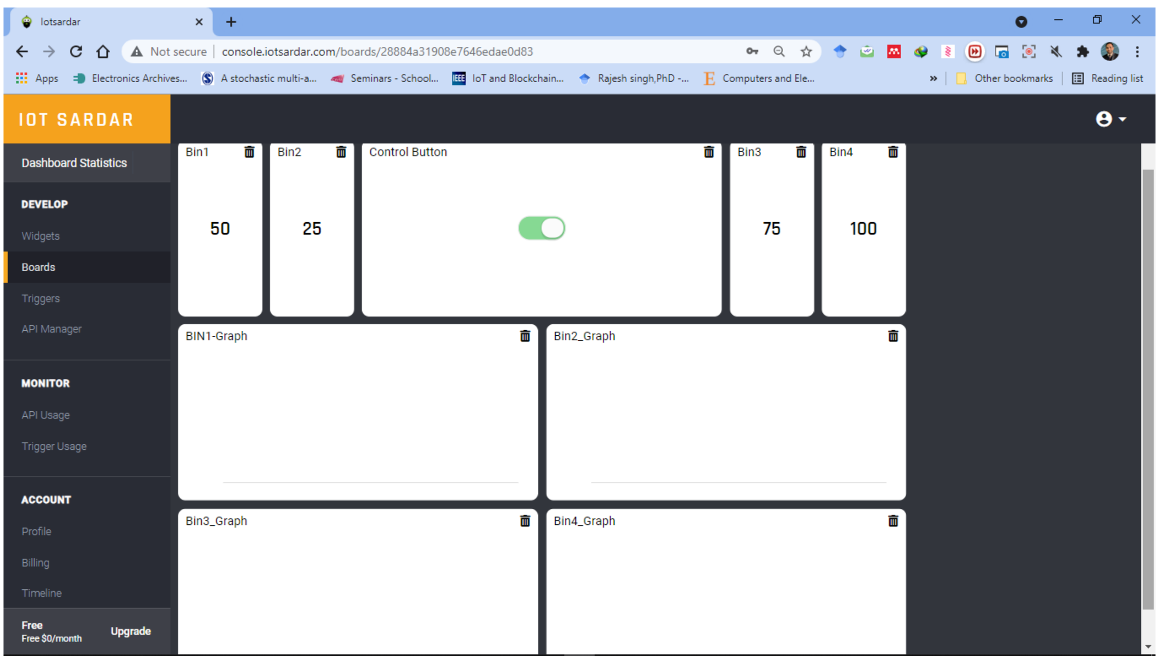

Figure 5.11 User Interface of Waste Management Server

The threshold value is used for monitoring the status of the bins in terms of percentage. The mapping feature is used for mapping the emptiness of the bin with 100%. The mapping feature also avoids data redundancy by analyzing the present distance and previous distance. In case the present distance and previous distance are the same then the sensor node doesn't send the data to the gateway. On other hand, if the present distance and previous distance is greater or lesser than 5 CM, then the sensor node maps the emptiness of the bin with 100% and transmits it to the gateway. On another hand during data transmission, the data is secured with symmetric encryption. The symmetric encryption comprises the private key, and it is logged into the sensor node and gateway for encryption and decryption of the data. The demand-on-transmission feature enables the gateway to request the data from the sensor node on demand.

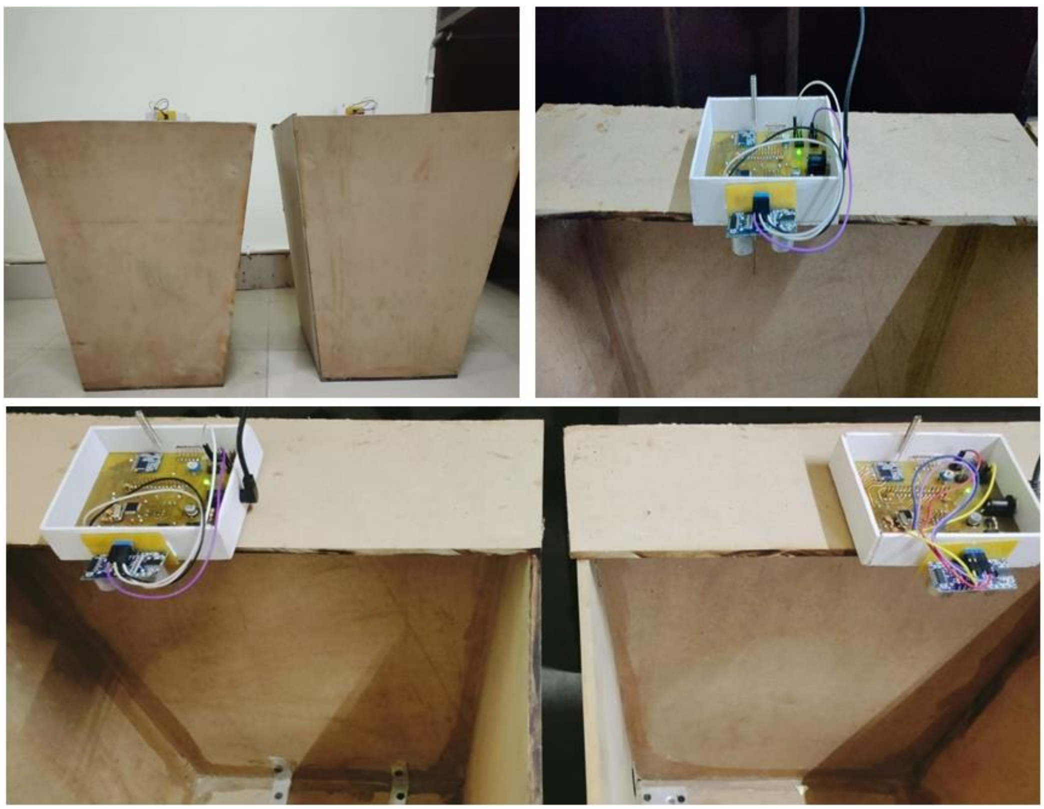

Figure 5.12 Customized Hardware Embedded in the Bins

5.6.1 Working Process of the Sensor Node and Gateway

In this section, the working process of the sensor node and gateway is discussed after logging the optimal parameters that are concluded from the simulation (Chapter 4).

a) Sensor node

The complete working process of the sensor nodes to transmit the sensory data to the gateway is illustrated in figure 5.13. The sensor node initiates the SPI of the 433 MHz

LoRa module along with the ultrasonic sensor. The sensor node receives the sensor data through the ultrasonic sensor.

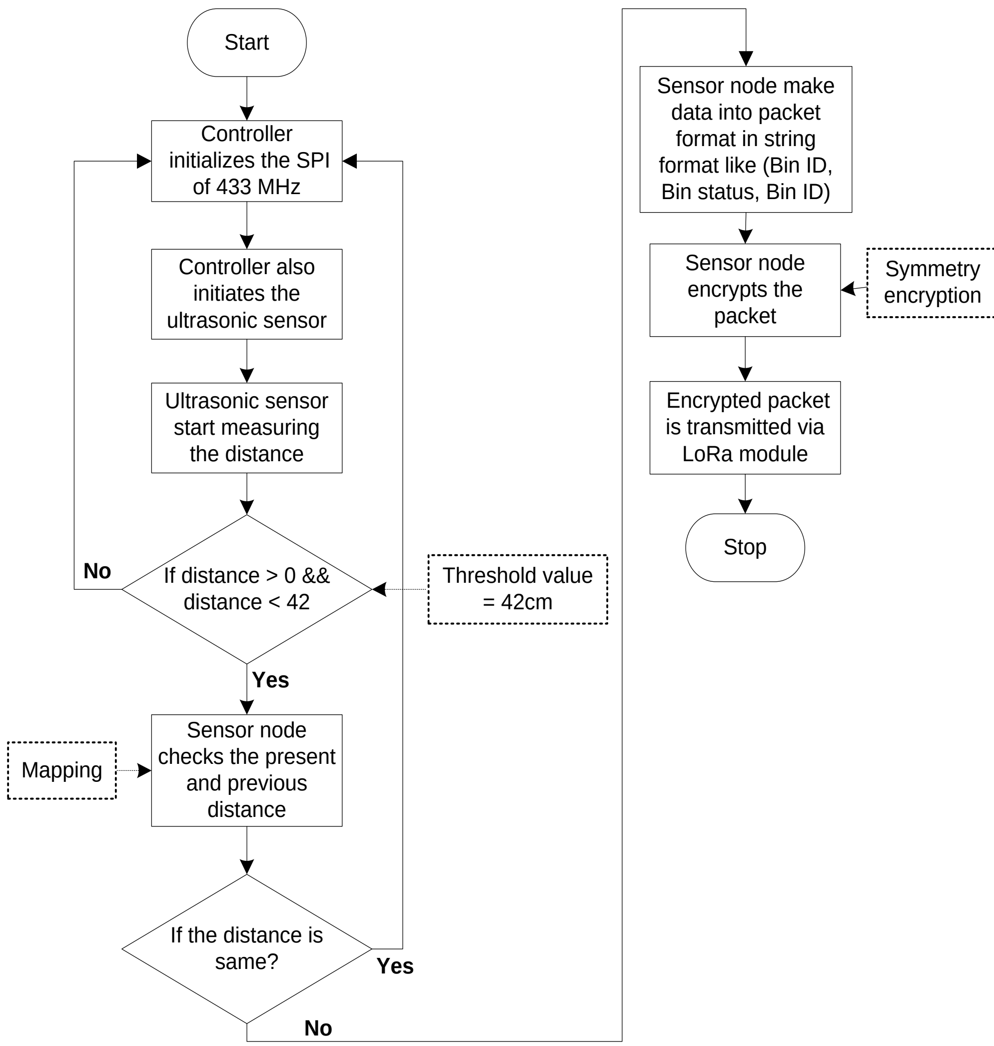

Figure 5.13 Overall Working Process of the Sensor Node

The sensor node transmits the sensor data only if it satisfies this condition "If distance > 0 && distance < 42". The emptiness of the bin is mapped with 100% based on the threshold value. As discussed in section 5.5, the sensor node analyzes the present distance and previous distance and converts the data into a packet format, only if both distances are not the same. The format of the packet is Bin ID, Bin status, Bin ID. The symmetric encryption in the sensor node encrypts the packet and transmits it to the gateway.

b) Gateway

The complete working process of the gateway from the sensor node to the gateway is illustrated in figure 5.14. The gateway checks the packet received from the LoRa module of the sensor node after the initialization of the 433 MHz LoRa module**.** The received packet is decrypted using the private key and visualizes the packet data like Bin ID, Bin status, RSSI, and SNR on the LCD. The received packet is transmitted to the ESP 8266 Wi-Fi module which is connected to the ATMega 328P controller. The Wi-Fi SSID and password embedded in the ESP 8266 Wi-Fi module enable to connect to the internet. The API of the waste management server embedded in the gateway enables the log of the received packets on the server in JSON format. The APIs of the waste management server is embedded in the gateway which enables the sensor node to log the sensory data into a custom waste management server. The sensor node and gateway are supplied with an external power supply for logging the real-time sensor values of bins in the waste management server and also evaluating the performance of hardware along with the waste management server.

The status of the three bins from the sensor node is visualized on the LCD of the gateway (figure.5.15). The status of bins is displayed in the following format BIN ID, emptiness (%) of the bins. Further, the ESP 8266 Wi-Fi module connects to the internet and displays the sensor data in the graphical representation (figure 5.16). The RSSI and SNR values are two values that evaluate the signal strength of the received signal from the sender (sensor node) and it is visualized on the widgets. The RSSI value represents the received signal from the sender, and it is used to determine the effectiveness of a receiver (gateway) to hear a signal from a sender (sensor node). RSSI values logged in the waste management server denotes that the receiver can hear the signal from the sender as RSSI value recorded are -55 dBm, -52dBm, and -52 dBm [RSSI value close to 0 is a good signal and RSSI value close to 100 is weak signal]. SNR value indicates the strength of the signal received at the receiver (gateway) from the transmitter (sensor node) over noise floor level.

SNR values recorded in the waste management server are 9.75 dB, 9.50 dBm, and 10.25 dBm. These values indicated that the received signal is noise-free.

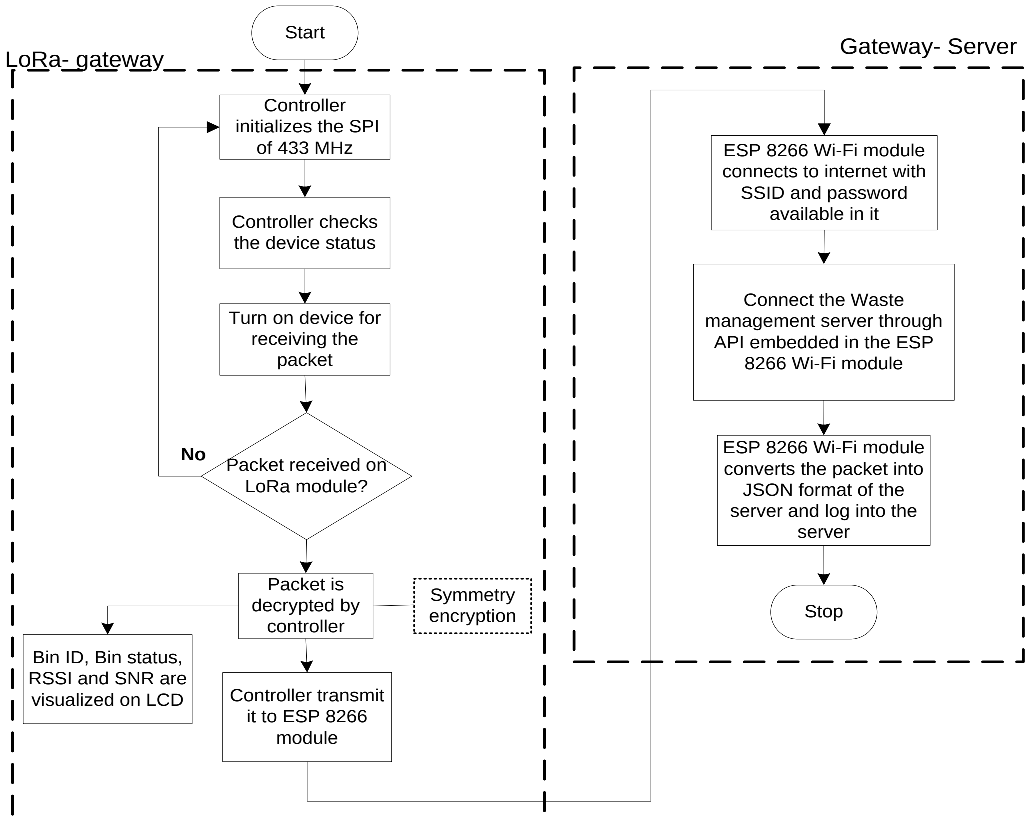

Figure 5.14 Overall Working Process of the Gateway

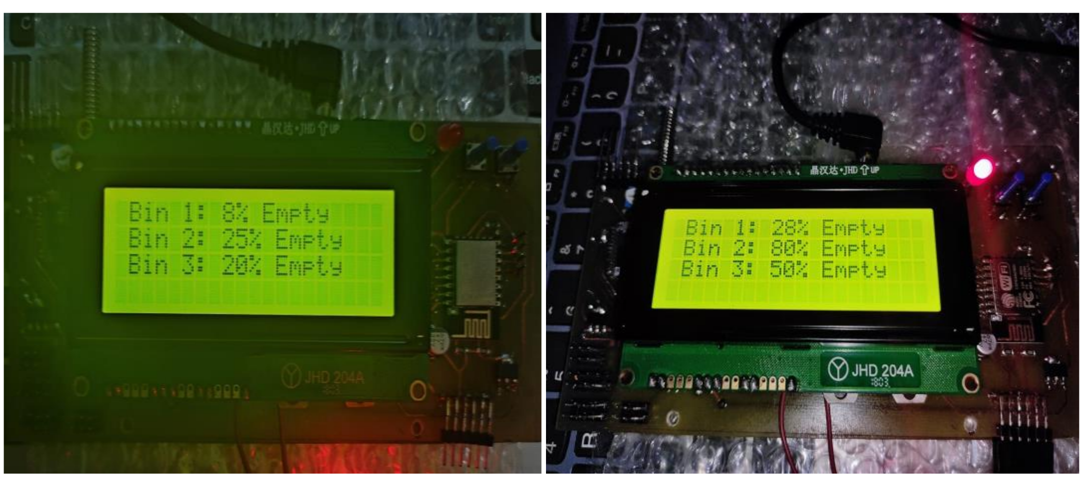

Figure 5.15 Sensor Data Visualization in Gateway

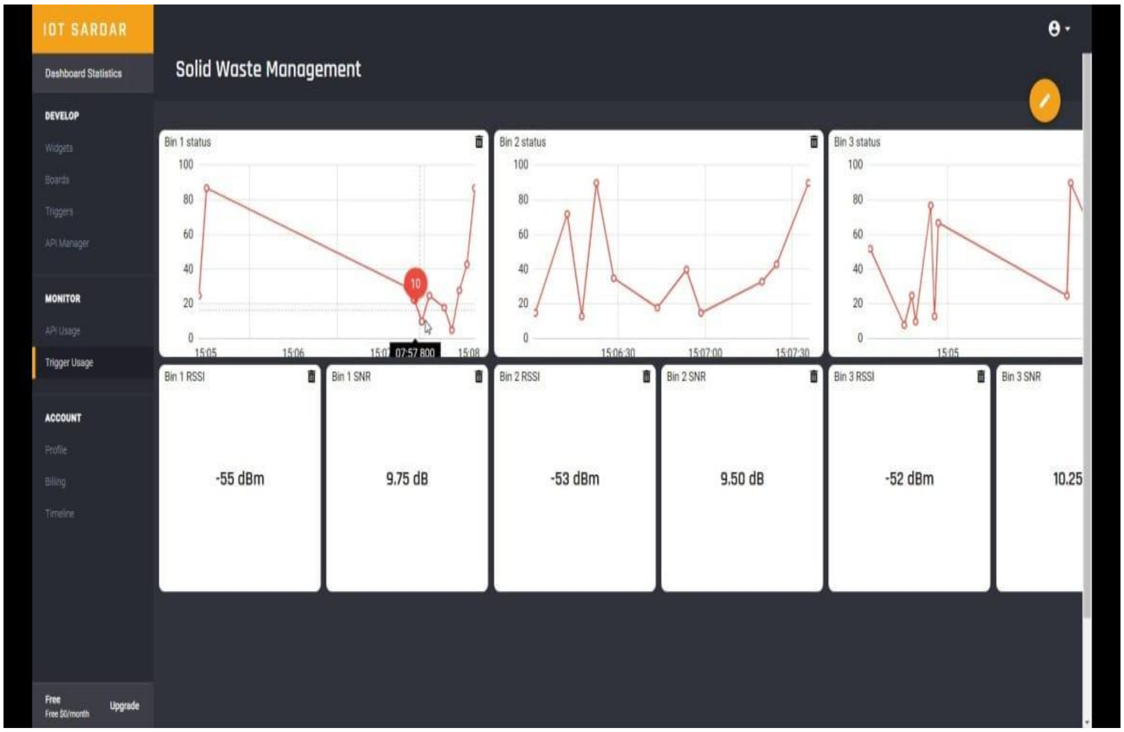

Figure 5.16 Sensor Data Visualization in Waste Management Server

5.7 Chapter Summary

In this chapter, the development of a customized cloud server is discussed. The customized waste management server is developed to monitor, log, and visualize the sensor data of the bins through LoRa communication and gateway. An architecture is proposed for explaining the interfacing of the sensor node with gateway and gateway with cloud server. Initially, the customized sensor node and gateway are tested on an open-source cloud platform like Blynk and Thingspeak server. The test results conclude that ESP8266 based gateway is connected to both servers and also can log and visualize the sensory data of the bins. The customized waste management server is developed with the Node.js, Mongo database, and angular framework with the hardware configuration of 1 GB RAM, 1 core processor, 20 GB SSD. The customized cloud server is developed and integrated with the customized hardware and also visualized real-time sensor data of the bins.

A research article is published about the integration of hardware with Blynk and the **publication** is: Shaik Vaseem Akram, Rajesh Singh, Anita Gehlot, Amit Kumar Thakur, "Design and Implementation of a Wide Area Network Based Waste Management System Using Blynk and Cayenne Application" is published in the Iranian Journal of Electrical and Electronic Engineering [Scopus].

Chapter 6

Blockchain Integration

In this chapter, the integration of the blockchain with the waste management server for implementing the waste-to-money model is described. The significance of integrating blockchain with waste management server is also addressed. The architecture and implementation of the blockchain with waste management server through local API are presented in detail.

6.1 Significance of Blockchain for Solid Waste Management

Solid waste management comprises distinct activities like collection, transportation, recycling, and disposal. At present there is a requirement of enhancing the mechanism of solid waste management for tracking, monitoring, and managing the waste, to gain maximum benefits from it through reuse and recycling (N. Sharma et al., n.d.). According to previous research, one of the reasons for the local administration is a lack of reliable information about the quantity and classification of garbage (Srivastava et al., 2015). Many studies have implemented different methodologies and mechanisms for resolving these challenges. Yet there is a possibility of enhancing the administration of municipal authorities by visualizing the real-time data for quantity, characterization, and transactions. At present IoT and cloud servers are widely adopted in solid waste management to provide real-time data, however, there is a need for a mechanism that can enhance the security and authentication of the data received from the IoT devices.

According to (Rybnytska et al., 2018), blockchain technology may be used to create an automated payment system for collecting garbage from anybody. A mobile app will be used to process the payment into the municipal administration's account after disposing the waste in the vehicle. To implement a payment system, the main parameter that is considered is security and authentication. Blockchain is an innovative technology which is proven to be secured for implementing the payment system reliably. The public key cryptography, hash function, and distributed ledger are the unique feature of blockchain to implement payment systems (P. K. Sharma & Park, 2018b). A recent study also suggested a business model handle and enhance the activities of solid waste management for minimizing the effects on the environment (P. Gopalakrishnan & Ramaguru, 2019). A study proposed a business model for enhancing the activities of solid waste management. The business model is recognized as waste-to-model where a decentralized system is built for managing the local solid waste management activities (P. K. Gopalakrishnan et al., 2020). In this model, a recycling unit and collection unit pay a value for the quantity of waste disposed by an individual to them. To implement this model effectively, data authentication, and a secure payment system are significant elements. The data authentication and secure payment system are possible with blockchain technology, as it authenticates the real-time data received from the IoT-enabled devices that are deployed in the bins of individuals. The present research focuses on implementing the blockchain with IoT-enabled hardware and blockchain technology. To achieve it, a customized sensor node and gateway are developed with SX 1278 module. Moreover, with the assistance of the ESP 8266 Wi-Fi-enabled gateway, the sensory data (like weight and level measurement) from the sensor node is logged in the waste management server. A customized waste management server is developed to integrate blockchain technology to realize the waste-to-money model with real-time data.

6.2 Architecture of Waste-to-Money Model

The integration of blockchain with waste management server is implemented for realizing the waste-to-money model. Waste-to-money model is a concept that is part of the solid waste management, in which the points will be generated on the basis of amount of the waste generated in the bins. Blockchain is utilized to validate the received sensor data and generate transactions and points for the generated waste in a secure manner. To integrate blockchain with IoT-enabled waste management server architecture is proposed in this chapter, as shown in figure 6.1. The blockchain implementation with the waste management server is performed through a local network API. Different components make up the architecture, including a data source made up of a gateway, IoT devices, a fog node, an edge node, and a cloud server. API is used to transmit the data of IoT devices to the cloud server and interface the cloud server with blockchain through API. New transactions are created as a result of the entering data, and a new block is formed. This transaction is sent to several nodes for mining. The miners (nodes) in the solid waste management system perform the task of mining during the creation of transactions.

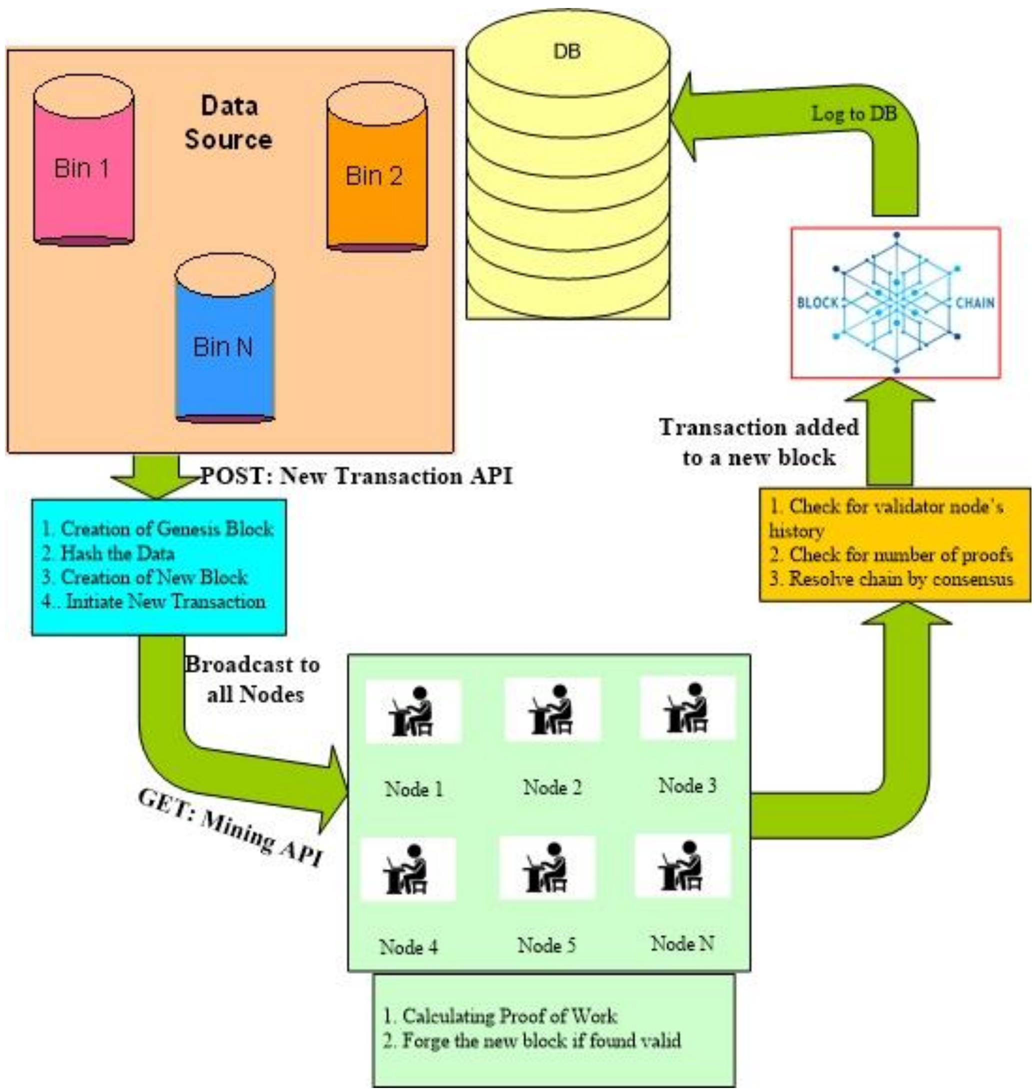

Figure 6.1 Interfacing of Blockchain to Connect Cloud through API

For validation, miners used the PoW algorithm provided in the nodes. If the transaction is legitimate, then the transaction is updated to the new blockchain. Furthermore, the fog node validates the number of proofs performed by nodes. While verifying nodes, the multiple chains resolved by nodes through consensus are taken into account. If the nodes are legitimate, the transaction is restructured with a new block and logged in the database. As the suggested solid waste management system is centered on a private blockchain and is controlled by one entity.

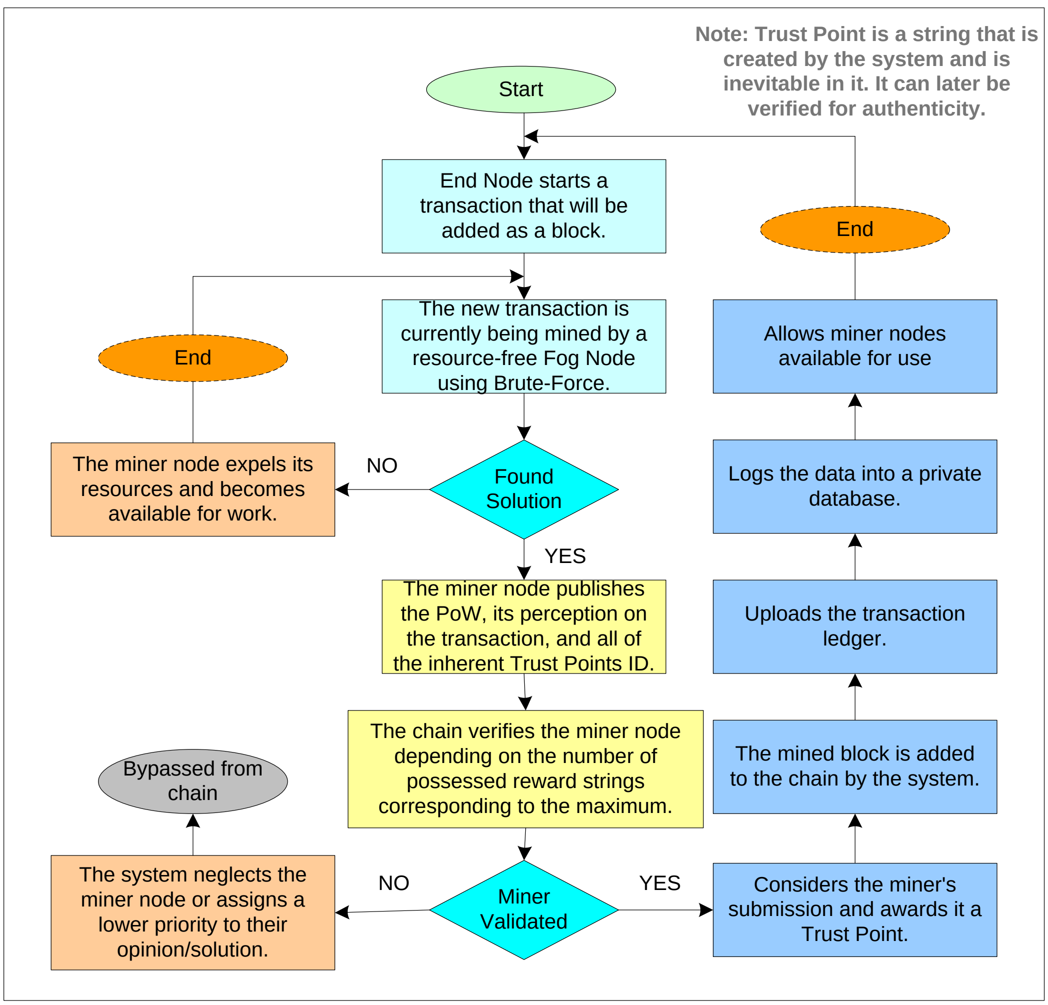

Figure 6.2 Method for Miner Verification in Private Blockchains with Trust Point

The additional contributions in the private blockchain are valid through the proposed method (figure 6.2). Generally, this method is suggested for miner node authentication in private blockchain networks. As a result, the system introduced a security attribute called Trust Point, which is a one-of-a-unique key produced by the system for paying mining fog nodes centered on the performance of their PoW, comparable to the rewards given to miner nodes in public blockchain networks.

The system initializes the Trust Point count for all its fog nodes to 1 at the first stage of the blockchain network's deployment. The miner fog nodes are rewarded with Trust Points in each event of successful PoW submission and also for identification of the latest block's hash. The fog nodes that are available at the time, begin the mine of the latest transaction with brute force, and further, it identifies the latest transaction block and validates its hash. When identified, the miner fog nodes provide the PoW as well as their current trust point score to the blockchain. The authentic fog nodes that are continuously mined for the network have a higher Trust Point score. At the same time algorithm ultimately evaluates the submitted PoW as authentic or irrelevant based on their trust point score. In case, if the trust point score is very less, then the blockchain considered it as suspect and stacks into lower priority. The mined block by the miner is updated to the blockchain with a trust point after validation of the block. Here the transaction is revised, and it is logged into the database (DB). In some cases, additional nodes are added to the same blockchain network; in that case, a node in the network records the adjacent nodes and updates them in the network while performing the consensus method. As a result, a few extra endpoints are necessary, which are as follows:

/nodes/register to allow a list of recent nodes in URL format
/nodes/resolve to build a consensus mechanism that resolves any disagreements to verify that a node's chain is accurate.

The first step, ***valid chain()***, examines whether a chain is genuine and passes through each node to examine both hashes and proof. ***resolve conflicts()*** is a procedure that verifies all of the adjacent nodes for loops, downloads, and activities. If the value of ***valid chain ( )*** is greater then it gets replaced. It is now possible to use another machine while selecting and switching various nodes on the network. Alternatively, users can swap operations in a similar environment with different ports. Switched to a different node on a different port on the system and captured it with the new node. Ultimately, two nodes are accessible: http://localhost:5000 and http://localhost:5001.

6.3 Real-Time Experiment

The system is built on a computer with an Intel Core i5-8250U CPU@ 1.60 GHz (8 CPUs), 12288 MB RAM, and 1.8GHz memory of Windows 10 (64-bit OS). The automatic reward is implemented through python programming as algorithmic architecture and data technique (figure 6.3). A flask-based server framework is utilized to develop the website, as well as all network requests for decentralized architectural style operations such as latest transaction creation, mine, chain fetch, and so on.

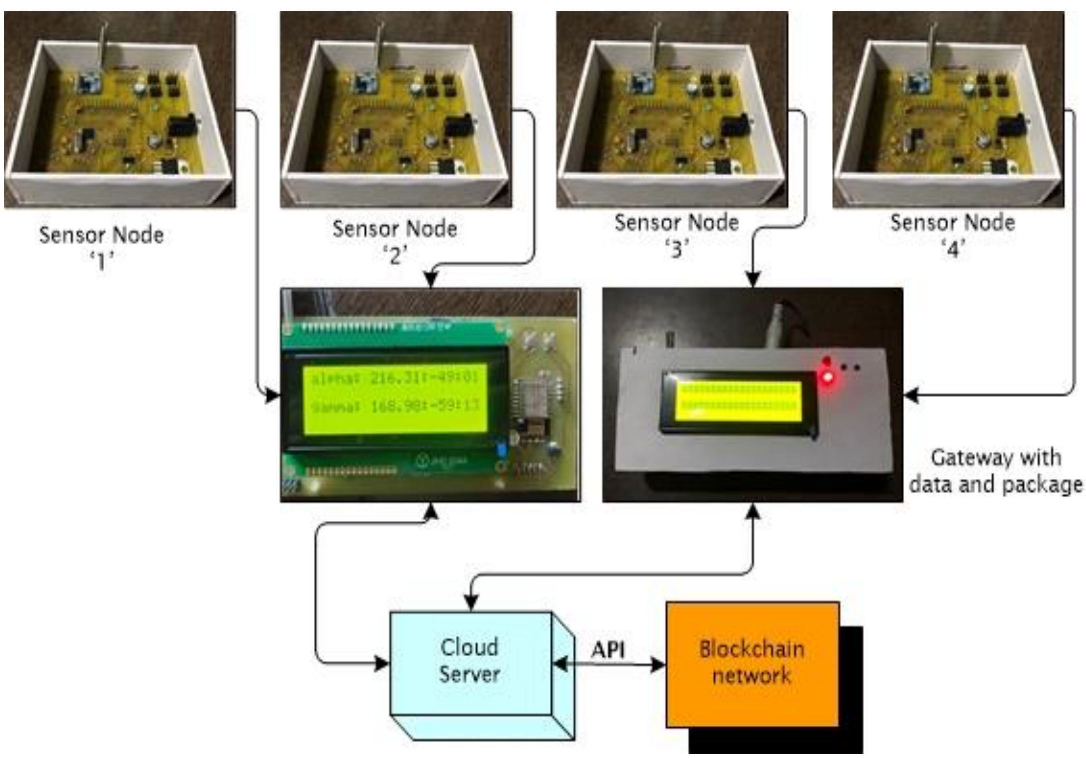

Figure 6.3 Hardware Implementation in Real-Time

The VS code editor is used for testing, development, and debugging of the proposed system components (*Visual Studio Code - Code Editing. Redefined*, n.d.). Postman is used to test the APIs designed for network executions (*Postman API Platform | Sign Up for Free*, n.d.). The customized gateway and sensor node with an ATMega328P microcontroller and LoRa connectivity is used for real-time implementation. A level measurement sensor and a weight sensor are applied in sensor nodes to sense the level and quantity of waste in the bin. The reward mechanism is activated on basis of the sensory data and the gateway serves as a bridge between the bin and the cloud through LoRa and the internet. It is the function of API to link the cloud server to the blockchain network. To develop the proposed reward system on Web API, a Python-based flask framework is utilized. Flask is a micro-framework which maps python endpoint functions, and it enables it to connect with the blockchain via HTTP requests (*Welcome to Flask — Flask Documentation (2.0.x)*, n.d.). GET and POST is two HTTP methods for the web API. The three methods are followed to create transactions and mine the latest block, as shown below.

transactions/new To introduce a new transaction into the blockchain.
/mine to notify the flask server when the latest block is mined.
/chain to recover the whole network of blockchain

Creates a new instance of **Node**.
Provide the node with a random name.
Create an instance of our **Blockchain class.**
Create a **GET** request for the **/mine endpoint**.
Create the **/transactions/new endpoint**, for **POST** request
Create the **/chain endpoint,** retrieve the network of blockchain
The flask server is running on port 5000.

The server is constructed and initiates the blockchain to execute solid waste management transactions. The functions required to construct a blockchain (figure 6.4).

The hash algorithm is created using the methods mentioned in figure 6.5 after the creation of the blockchain. When the blockchain gets data on the amount of waste generated by IoT devices, it generates a block with the functions represented in Figure 6.6. Simultaneously, a new transaction is generated using the procedures indicated in Figure 6.7. During creating the transaction, the parameters included are inspectorID (credentials of the inspector), a user (credentials of the user Recipient), and weight (amount of weight). After generating a new transaction, the PoW consensus mechanism is used by miners for validating the new transaction. The miner assesses the transaction on the basis of instructions presented in the function (figure 6.8).

```
class blockchainClass:
    def __init__(self):
        self.current_transactions = [ ]
        self.chain = [ ]
        self.nodes = set( )

        # Create the genesis block
        self.new_block(previous_hash='1', proof=100)
```

Figure 6.4 Building Blockchain

```
def createHash(block):
    block_string = json.dumps(block, sort_keys=True).encode()
    return hashlib.sha256(block_string).hexdigest()
```

Figure 6.5 Hash Algorithm

```
def createNewBlock(self, proof, previous_hash):

    block = {
        'index': len(self.chain) + 1,
        'timestamp': time(),
        'transactions': self.current_transactions,
        'proof': proof,
        'previous_hash': previous_hash or self.hash(self.chain[-1]),
    }
    self.current_transactions = []
    self.chain.append(block)
    return block
```

Figure 6.6 Creating a New Block

The transaction that the miner approves is represented in Figure 6.9. The amount of waste in the bins is displayed in the flask server. POST is used to add a new transaction, while GET is used to mine the node. The parameters contained during the transaction's creation, as well as the method for interacting with the blockchain, are shown below.

```
def newTransaction(self, inspectorID, user, weight):
    self.current_transactions.append({
        'inspectorID': inspectorID,
        'user': user,
        'weight': weight,
    })

    return self.last_block['index'] + 1
```

Figure 6.7 Creating a New Transaction

```
def proof_of_work(self, last_block):

    last_proof = last_block['proof']
    last_hash = self.hash(last_block)

    proof = 0
    while self.valid_proof(last_proof, proof, last_hash) is False:
        proof += 1

    return proof
```

Figure 6.8 Proof of Work

inspectorID: Credentials of inspector

user: Credentials of the user Recipient

weight: Amount of weight

Interface with **blockchain**

Use cURL or **Postman** with a start-up server to connect to our **API** through the internet.

To mine a block, execute a **GET** request. **http://localhost:5000/mine**

By sending a **POST** request to start a new transaction.

http://localhost:5000/transactions/new

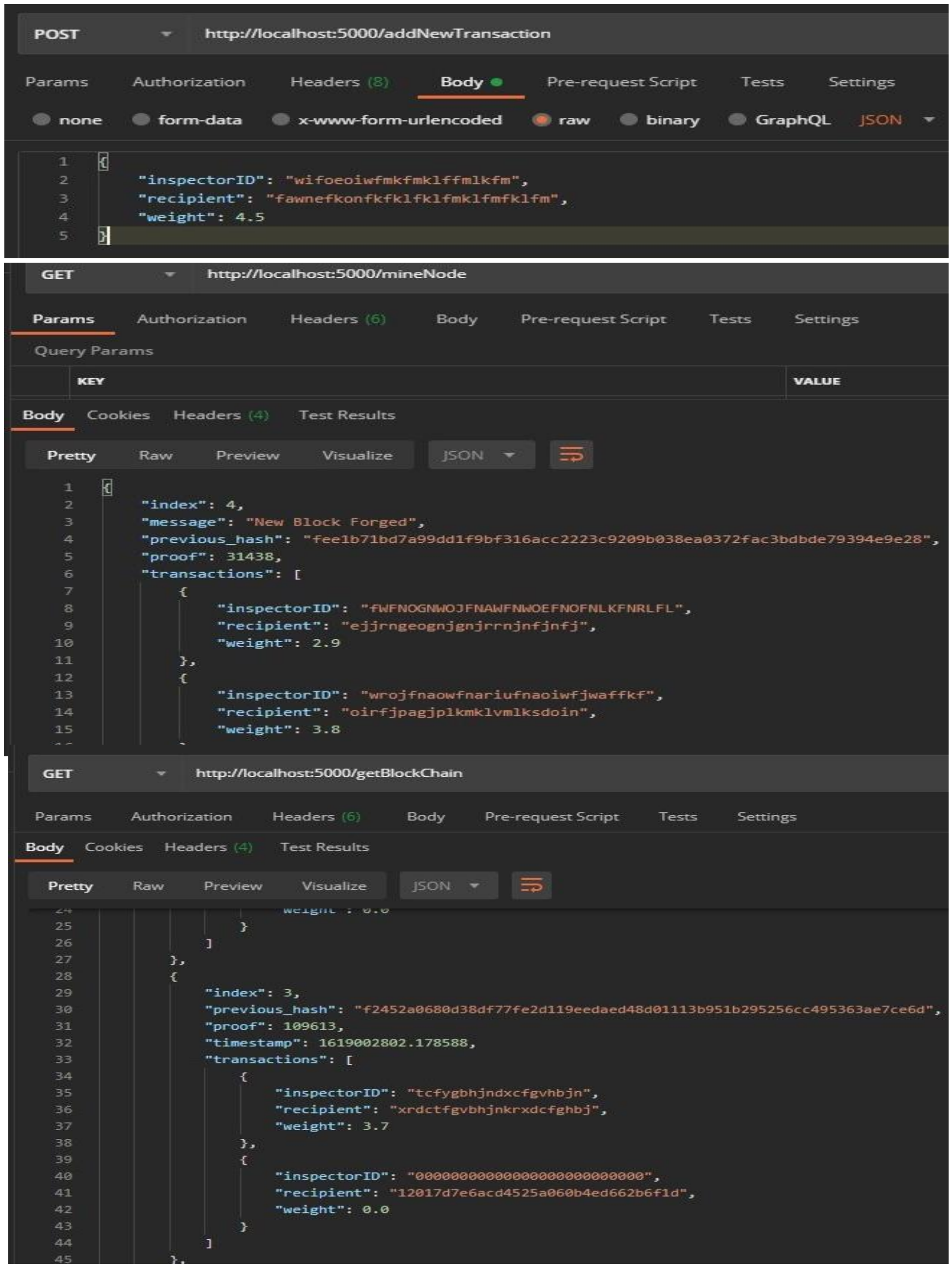

Figure 6.9 Blockchain Server Visualizes the Quantity

The automatic reward system on the basis of sensory data is realized with the method described in figure 6.10. Blockchain technology is a decentralized network in which users or participants are connected in a decentralized manner. From the figure, the user may be three participants including A, B, and C. In case, A is assumed as the user, then the data regarding the quantity of waste is shared among the three participants. As discussed in section 1.4, the public key in the blockchain comprises data related to the source and destination. The data distributed by ‘A’ consists of ‘B’ public key, so the miners of ‘C’ ignore the data. Now, ‘B' miners assess the information based on certain characteristics such as bin ID and trash amount. The blockchain executes the amount to the ‘A' after miners evaluate on the basis of sensory data.

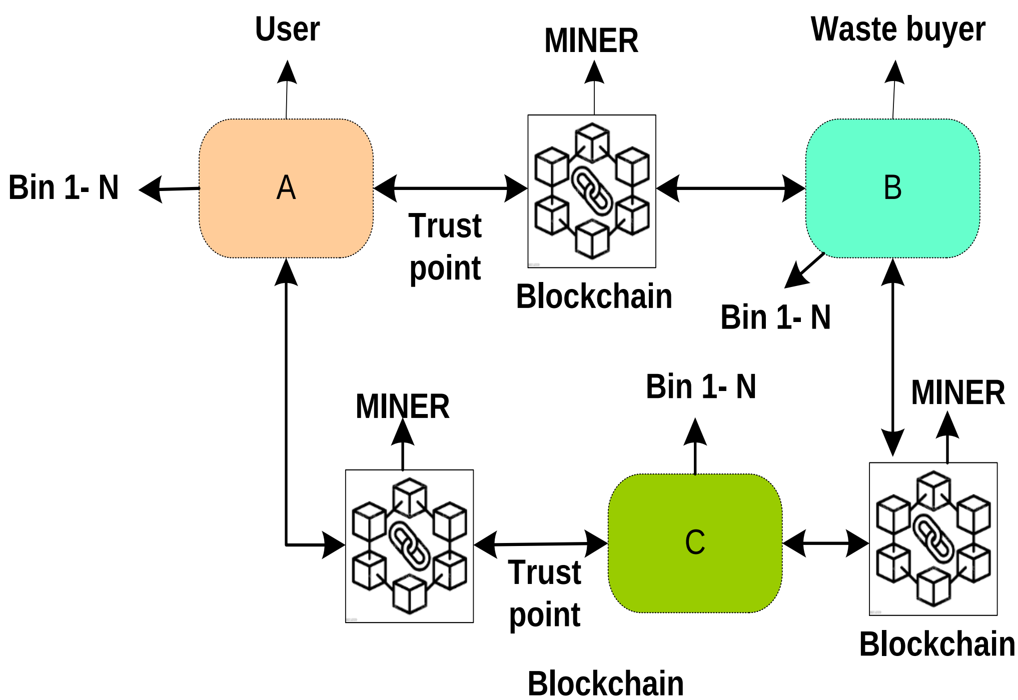

Figure 6.10 Working flow of Automatic Reward System

Table 6.1 summarizes past research on the use of blockchain in solid waste management. Previous research indicated that blockchain technology will improve solid waste management operations in the area of tracking, data security, and transparency. Furthermore, the combination of IoT and blockchain empowered us to create a real-time system to implement the reward. The comparison is based on many criteria such as the reward system, aim, API, framework, and hardware. Only a few prior studies have applied the blockchain effectively, while others have used solid waste management as a pilot study to evaluate the blockchain. The limited previous studies have implemented customized hardware to acquire real-time.

Table 6.1 Comparison with Previous Studies based on Blockchain for Solid Waste Management

Research	Function	Framework	Hardware
(Lamichhane, 2017)	an architecture is applied for combining IoT and blockchain	Blockchain and IoT enabled	In place of actual hardware, simulation is used
(P. K. Gopalakrishnan et al., 2020)	Enhancing the conventional system in terms of distributing information	Decision-making architecture for selection of service	Hardware implementation is lacking
(P. K. Gopalakrishnan et al., 2021)	Examining the life cycle of waste	Blockchain framework for the municipality	Hardware implementation is not carried out
(Ongena et al., 2018)	A research design technique is utilized to develop a blockchain-based waste management system.	A case study for cross waste	No software and practical implementation
(França et al., 2020)	In a small Brazilian town, blockchain is being used to replace green money in solid waste management.	Ethereum centered digital architecture for solid waste management	No hardware implementation

6.4 Chapter Summary

In this chapter, the integration of blockchain technology in solid waste management is addressed. A Waste-to-money model that integrates the IoT-enabled hardware and blockchain is explained. An architecture is implemented in this chapter for realizing the waste-to-money model on basis of real-time sensors data such as the quantity of garbage and level of waste with the flask server, and a local network (API). A real-time experiment is carried out to check the performance efficiency of the proposed architecture and it concludes that the weight sensor data is generating new transactions in the network of blockchain. A technique is also proposed to authenticate miners on a private blockchain through a trust point. The integration of blockchain with the customized hardware is realized and waste-to-money model is also achieved with integration in real-time.

A research article is published with relevant to the integration of hardware with blockchain and **publication:** Shaik Vaseem Akram, Sultan S. Altamirano, Rajesh Singh, Mamoon Rashid, Anita Gehlot, Ahmed Saeed AlGhamdi, Deepak Prashar, “Blockchain-enabled Automatic Reward System in Solid Waste Management” is published in Security and Communication Networks, Hindawi (SCI).

Chapter 7

Conclusion and Future Scope

In recent years, few effective solutions have been developed for real-time monitoring of solid waste by employing information and communication technology. It has been observed from previous literature that the IoT is an emerging technology to monitor the different activities in solid waste management such as i) garbage level, ii) location of containers, and iii) shortest route. Moreover, the integration of blockchain with IoT has also shown a significant path for a few years which generates the transactions among the different IoT devices. Real-time hardware based IoT devices for effective monitoring of solid waste are still an open research challenge. The implementation of a LoRa-based IoT network and blockchain for communication and executing the transactions based on real-time data is also a limitation in solid waste management.

In the first objective, the scalable architecture is proposed for monitoring the solid waste management system that integrates the real-time hardware with LoRa communication protocol and lightweight blockchain technology. As part of real-time implementation, a customized IoT-enabled hardware with ATMega328P microcontroller, SX 1278 LoRa module, and ESP 8266 Wi-Fi module is developed. The SX1278 LoRa transceiver module incorporated in the customized sensor node establishes the own network to connect to the gateway. The key purpose of the gateway is to communicate the data over multiple communication protocols, in which the SX 1278 LoRa transceiver is utilized for the collection of the data from the sensor node. The controller sparks the ESP 8266 Wi-Fi module to transmit the data over IP. The outcome of this objective is: a customized IoT enabled hardware i.e., sensor node and gateway are designed to sense filling level of the bins on cloud server and also for integrating hardware with the blockchain.

In the second objective, the simulation process in the virtual environment is carried out for selecting the optimal parameters before the establishment of the LoRa network between the bins with customized real-time hardware. The pre-defined parameter such as BW, SF, and CR are utilized to estimate the performance of the LoRa network. Furthermore, the performance efficacy of the LoRa network is evaluated by varying pre-defined parameters into the energy consumption of nodes, bitrate, receiver sensitivity, link budget, and battery life of sensor nodes. Moreover, a comparative analysis is done to check the performance of selected parameters for the LoRa communication protocol. From the analysis, it has been concluded that the optimal parameters for the real-time implementation of customized hardware to obtain sensor data with reliable LoRa network are BW value of 125kHz, the SF is 7, and the CR is 4/8. The contribution of this objective is: performance analysis of LoRa network is performed and finalized the optimal parameters for effective and reliable real-time implementation of customized hardware with LoRa network to obtain sensor data from the bins.

In the third objective, the selected optimal parameters from the virtual simulation process are further logged in the customized real-time hardware for real-time implementation with the aid of Arduino IDE and C++ programming language. In addition, the features such as mapping, demand on transmission, and symmetry encryption are also logged along with the optimal parameters in the customized real-time hardware. The function of integrating mapping is to overcome the data redundancy during the transmission from the sensor node to the gateway. While the demand on transmission is used to enable the gateway for triggering the data from the sensor node. On other hand, the data is encrypted and decrypted by using the symmetry encryption technique. The real-time data of customized hardware from the sensor node through the Wi-Fi-assisted gateway is visualized on the built customized cloud server. The customized cloud server is further integrated with the lightweight blockchain to generate rewards on the basis of sensory data. The main aim of integrating lightweight blockchain with customized cloud server is to avoid the extra computational processing power. The outcome of this objective is: The customized cloud server is developed and integrated with the customized hardware and also visualized real-time sensor data of the bins on the customized cloud server.

In the fourth objective, the lightweight blockchain and the customized cloud server are integrated by using the flask platform to implement the waste-to-money model with customized hardware. The purpose of using blockchain technology in solid waste management is to generate an automatic reward for an individual on the basis of the amount of waste disposed of in the bin with security. The process of a reward mechanism is executed on the basis of real-time sensor data obtained from sensor nodes that are embedded in the bins. It has been concluded from the real-time implementation that every bin is generating a new transaction in the blockchain network. Once the miners are validating the transaction and a trust point is rewarded, a new block is added to the blockchain. The validation of the transactions by the miners is processed through a PoW mechanism. In this, the reward points are generated to an individual centered on the real-time sensor data obtained from the bins with blockchain technology. The contribution of this objective is: the integration of blockchain with the customized hardware is realized and waste-to-money model is also achieved with integration.

In the first objective the customized hardware is developed with advanced wireless long range communication protocol i.e., SX 1278 module. After the development of the customized hardware, the performance analysis is carried out to finalize the optimal parameters like SF, CR, BW that are required for the real-time implementation of customized hardware with LoRa network. The finalized parameters are integrated in the customized hardware and the developed customized cloud server is integrated with hardware to log the sensory data of the bins. The customized cloud server is integrated with blockchain through flask server, and a local network (API). The complete achieved objectives aim to realize waste-to-money model based on the quantity and filling level sensor data obtained from the hardware.

The current research achieved the implementation and integration of real-time customized hardware with LoRa network and blockchain technology in the solid waste management to enhance the solid waste management mechanism through wirelessly.

The contributions of the thesis have a future scope in the field of the solid waste management system that meets the United Nations sustainable development goals. In future work, the limitations of the proposed work along with the previous literature will be carried out. Some of the major challenges and limitations that need to be focused on in the future are enlisted below:

- ***Solid Waste Management System:*** In a solid waste management system, real-world case studies need to be tested for resolving the issues of waste generation and recovery in different countries.
- ***Blockchain for Circular Economy in Solid Waste Management:*** Blockchain can be implemented for realizing the circular economy in solid waste management, where every activity of solid waste management, like collection, transportation and recycling are distributed in the blockchain network.
- ***Machine Learning with Vision Node:*** The vision node with the machine learning algorithm empowers to implement a computer-based vision system to predict the generation of waste, characterization of waste with real-time series data.

List of Publications

Patents

1. Shaik Vaseem Akram, Rajesh Singh, Anita Gehlot, Lovi Raj Gupta, **“Hybrid Architecture for Waste Management System with LoRa and Blockchain”** and **application no**: 201911047534. [**Published**: 21/11/2019].

2. Vaseem Shaik Akram, Anita Gehlot, Lovi Raj Gupta, Rajesh Singh, Paramveer Kang, Prabin Kumar Das, “**A Vehicle Controller for Waste Collection with Geo Mapping**” and **patent no:** 357130. [**Granted:** 29/01/2021].

Journal Papers

1. Shaik Vaseem Akram, Rajesh Singh, Mohammed A. AlZain, Anita Gehlot, Mamoon Rashid, Osama S. Faragallah, Walid El-Shafai, Deepak Prashar, **“Performance Analysis of IoT and Long-Range Radio-Based Sensor Node and Gateway Architecture for Solid Waste Management is published in Sensors, MDPI (SCI)** with impact factor- 3.275. [**Published:** 14/04/2021] **[https://doi.org/10.3390/s21082774**].

2. Shaik Vaseem Akram, Sultan S. Alshamrani, Rajesh Singh, Mamoon Rashid, Anita Gehlot, Ahmed Saeed AlGhamdi, Deepak Prashar, “**Blockchain-enabled Automatic Reward System in Solid Waste Management**” is published in **Security and Communication Networks, Hindawi (SCI)** with impact factor: 1.791. [**Published**: 06/09/2021]. [https://doi.org/10.1155/2021/6952121].

3. Shaik Vaseem Akram, Rajesh Singh, Anita Gehlot, Mamoon Rashid, Ahmed Saeed AlGhamdi, Sultan S. Alshamrani, and Deepak Prashar. **"Role of Wireless Aided Technologies in the Solid Waste Management: A Comprehensive Review**." Is

published in **Sustainability, MDPI,** (SCI) with impact factor-3.251. [**Published:** 26/11/2021]. [https://doi.org/10.3390/su132313104]

4. Shaik Vaseem Akram, Rajesh Singh, Anita Gehlot, Amit Kumar Thakur, "**Design and Implementation of a Wide Area Network Based Waste Management System Using Blynk and Cayenne Application**" is Published in the **Iranian Journal of Electrical and Electronic Engineering** (SCOPUS) with SJR of 0.187. [**Published**: 23/01/2021], [**http://ijeee.iust.ac.ir/article-1-1941-en.html**].

5. Shaik V. Akram, Praveen K. Malik, Rajesh Singh, Anita Gehlot, Sudeep Tanwar, "**Adoption of blockchain technology in various realms: Opportunities and challenges"** is published in **Security and Privacy** [Wiley Online Library]. **Published**: 15/04/2020]. [**https://doi.org/10.1002/spy2.109**]

Conferences

1. Shaik Vaseem Akram, Rajesh Singh, Anita Gehlot, "**Raspberry Pi based Smart Waste Management System using Internet of Things"** is presented and published in the **International Conference on Intelligent Circuits and Systems (ICICS) 2020 [https://doi.org/10.1201/9781003129103].**

2. Shaik Vaseem Akram, Rajesh Singh, Anita Gehlot, **"Long-Range Radio and Vision Node-based Waste Management System**" is presented and published in the **Intelligent Communication, Control and Devices (ICICCD) 2020**. [**Published:** 26/07/2021]. [**https://link.springer.com/book/10.1007/978-981-16-1510-8].**

Chapters

1. Shaik Vaseem Akram, Rajesh Singh, Anita Gehlot, "**Development of Solar Assisted Bins Using XBee and LoRa network for waste management application"** chapter is published in the book "Energy harvesting Technologies for powering the WPAN and IoT devices for industry 4.0 up gradation".[**Published:** April 2020].

2. Shaik Vaseem Akram, Rajesh Singh, Anita Gehlot, "**Wireless Personal Area Network-based Waste Monitoring System using XBee and IoT**" chapter is published in the book "LoRA and IoT networks for applications in industry 4.0". [**Published:** April 2020].

Bibliography

Abdallah, M., Adghim, M., Maraqa, M., & Aldahab, E. (2019). Simulation and optimization of dynamic waste collection routes. *Waste Management and Research*, *37*(8), 793–802. https://doi.org/10.1177/0734242X19833152

Abdel-Shafy, H. I., & Mansour, M. S. M. (2018). Solid waste issue: Sources, composition, disposal, recycling, and valorization. In *Egyptian Journal of Petroleum* (Vol. 27, Issue 4, pp. 1275–1290). Egyptian Petroleum Research Institute. https://doi.org/10.1016/j.ejpe.2018.07.003

Addabbo, T., Fort, A., Mecocci, A., Mugnaini, M., Parrino, S., Pozzebon, A., & Vignoli, V. (2019). A LoRa-based IoT Sensor Node for Waste Management Based on a Customized Ultrasonic Transceiver. *2019 IEEE Sensors Applications Symposium (SAS)*, 1–6.

Adeofun, C. O., Achi, H. A., Ufoegbune, G. C., Gbadebo, A. M., & Oyedepo, J. A. (2012). Application of remote sensing and geographic information system for selecting dumpsites and transport routes in Abeokuta, Nigeria. *COLERM Proceedings*, *1*, 264–278.

Ahmed, S. M., Muhammad, H., & Sivertun, A. (2006). Solid waste management planning using GIS and remote sensing technologies case study Aurangabad City, India. *2006 International Conference on Advances in Space Technologies*, 196–200.

Akhtar, M., Hannan, M. A., Begum, R. A., Basri, H., & Scavino, E. (2017). Backtracking search algorithm in CVRP models for efficient solid waste collection and route optimization. *Waste Management*, *61*, 117–128. https://doi.org/10.1016/j.wasman.2017.01.022

Al Mamun, M. A., Hannan, M. A., Hussain, A., & Basri, H. (2015). Integrated sensing systems and algorithms for solid waste bin state management automation. *IEEE Sensors Journal*, *15*(1), 561–567. https://doi.org/10.1109/JSEN.2014.2351452

Alcarria, R., Bordel, B., Robles, T., Martín, D., & Manso-Callejo, M. Á. (2018). A blockchain-based authorization system for trustworthy resource monitoring and trading in smart communities. *Sensors (Switzerland)*, *18*(10). https://doi.org/10.3390/s18103561

Amal, L., Son, L. H., Chabchoub, H., & Lahiani, H. (2020). Analysis of municipal solid waste collection using GIS and multi-criteria decision aid. *Applied Geomatics*, *12*(2), 193–208. https://doi.org/10.1007/s12518-019-00291-6

Anagnostopoulos, T., Zaslavsky, A., Kolomvatsos, K., Medvedev, A., Amirian, P., Morley, J., & Hadjieftymiades, S. (2017). Challenges and opportunities of waste management in IoT-enabled smart cities: a survey. *IEEE Transactions on Sustainable Computing*, *2*(3), 275–289.

Anghinolfi, D., Paolucci, M., Robba, M., & Taramasso, A. C. (2013). A dynamic optimization model for solid waste recycling. *Waste Management*, *33*(2), 287–296.

Anh Khoa, T., Phuc, C. H., Lam, P. D., Nhu, L. M. B., Trong, N. M., Phuong, N. T. H., Dung, N. Van, Tan-Y, N., Nguyen, H. N., & Duc, D. N. M. (2020). Waste Management System Using IoT-Based Machine Learning in University. *Wireless Communications and Mobile Computing*, *2020*. https://doi.org/10.1155/2020/6138637

Apaydin, O., & Gonullu, M. T. (2007). Route optimization for solid waste collection: Trabzon (Turkey) case study. *Global NEST Journal*, *9*(1), 6–11.

Arebey, M., Hannan, M. A., Basri, H., Begum, R. A., & Abdullah, H. (2011). Integrated technologies for solid waste bin monitoring system. *Environmental Monitoring and Assessment*, *177*(1), 399–408.

Arebey, M., Hannan, M. A., Basri, H., Begum, R. A., & Abdullah, H. (2010). Solid waste monitoring system integration based on RFID, GPS and camera. *2010 International Conference on Intelligent and Advanced Systems*, 1–5.

Asghari, P., Rahmani, A. M., & Javadi, H. H. S. (2019). Internet of Things applications: A systematic review. *Computer Networks*, *148*, 241–261. https://doi.org/10.1016/j.comnet.2018.12.008

Aswin Raaju, V., Mappilllai Meeran, J., Sasidharan, M., & Premkumar, K. (2019, March

1). IOT based smart garbage monitoring system using ZigBee. *2019 IEEE International Conference on System, Computation, Automation and Networking, ICSCAN 2019*. https://doi.org/10.1109/ICSCAN.2019.8878742

Augustin, A., Yi, J., Clausen, T., & Townsley, W. M. (2016). A study of Lora: Long range & low power networks for the internet of things. *Sensors (Switzerland)*, *16*(9), 1–18. https://doi.org/10.3390/s16091466

Ayilara, M. S., Olanrewaju, O. S., Babalola, O. O., & Odeyemi, O. (2020). Waste management through composting: Challenges and potentials. *Sustainability (Switzerland)*, *12*(11), 1–23. https://doi.org/10.3390/su12114456

Balanis, C. A. (2012). *Antenna Theroy: Analysis and Design*.

Baygin, N., Baygin, M., & Karakose, M. (2019). Blockchain Technology: Applications, Benefits and Challenges. *2019 1st International Informatics and Software Engineering Conference (UBMYK)*, 1–5.

Ben-Daya, M., Hassini, E., & Bahroun, Z. (2019). Internet of things and supply chain management: a literature review. In *International Journal of Production Research* (Vol. 57, Issues 15–16, pp. 4719–4742). Taylor and Francis Ltd. https://doi.org/10.1080/00207543.2017.1402140

Bisinella, V., Götze, R., Conradsen, K., Damgaard, A., Christensen, T. H., & Astrup, T. F. (2017). Importance of waste composition for Life Cycle Assessment of waste management solutions. *Journal of Cleaner Production*, *164*, 1180–1191. https://doi.org/10.1016/j.jclepro.2017.07.013

Bitcoin: A Peer-to-Peer Electronic Cash System. (n.d.). Retrieved May 19, 2021, from https://bitcoin.org/en/bitcoin-paper

Bouras, C., Gkamas, A., Katsampiris Salgado, S. A., & Kokkinos, V. (2019). Comparison of LoRa simulation environments. *International Conference on Broadband and Wireless Computing, Communication and Applications*, 374–385.

Cavdar, K., Koroglu, M., & Akyildiz, B. (2016a). Design and implementation of a smart solid waste collection system. *International Journal of Environmental Science and Technology*, *13*(6), 1553–1562. https://doi.org/10.1007/s13762-016-0993-4

Cavdar, K., Koroglu, M., & Akyildiz, B. (2016b). Design and implementation of a smart solid waste collection system. *International Journal of Environmental Science and Technology*, *13*(6), 1553–1562.

Cerchecci, M., Luti, F., Mecocci, A., Parrino, S., Peruzzi, G., & Pozzebon, A. (2018a). A low power IoT sensor node architecture for waste management within smart cities context. *Sensors*, *18*(4), 1282.

Cerchecci, M., Luti, F., Mecocci, A., Parrino, S., Peruzzi, G., & Pozzebon, A. (2018b). A low power IoT sensor node architecture for waste management within smart cities context. *Sensors (Switzerland)*, *18*(4). https://doi.org/10.3390/s18041282

Chakole, S., Khadse, P., Shinganjude, S., Pimple, P., Shahane, S., & Mokhale, S. (2017). Real Time Smart City Garbage Collection and Monitoring System Using GSM and GPS. *International Research Journal of Engineering and Technology(IRJET)*, *4*(3), 1226–1229. https://irjet.net/archives/V4/i3/IRJET-V4I3291.pdf

Chalkias, C., & Lasaridi, K. (2009). A GIS based model for the optimisation of municipal solid waste collection: the case study of Nikea, Athens, Greece. *Technology*, *1*, 11–15.

Chang, N.-B., Lu, H. Y., & Wei, Y. L. (1997). GIS Technology for Vehicle Routing and Scheduling in Solid Waste Collection Systems. *Journal of Environmental Engineering*, *123*(9), 901–910. https://doi.org/10.1061/(ASCE)0733-9372(1997)123:9(901)

Chaudhari, M. S., Patil, B., & Raut, V. (2019). IoT based Waste Collection Management System for Smart Cities: An Overview. *2019 3rd International Conference on Computing Methodologies and Communication (ICCMC)*, 802–805.

Chen, G., Xu, B., Lu, M., & Chen, N.-S. (2018). Exploring blockchain technology and its potential applications for education. *Smart Learning Environments*, *5*(1), 1. https://doi.org/10.1186/s40561-017-0050-x

Cheng, H., & Hu, Y. (2010). Municipal solid waste (MSW) as a renewable source of energy: Current and future practices in China. *Bioresource Technology*, *101*(11), 3816–3824.

Chinnathurai, B. M., Sivakumar, R., Sadagopan, S., & Conrad, J. M. (2016). Design and implementation of a semi-autonomous waste segregation robot. *Conference Proceedings - IEEE SOUTHEASTCON*, *2016-July*. https://doi.org/10.1109/SECON.2016.7506679

Christidis, K, & Devetsikiotis, M. (2016). Blockchains and Smart Contracts for the Internet of Things," in IEEE Access, vol. 4, no. , pp. 2292-2303, 2016. *IEEE Access*, *4*, 2292–2303. https://doi.org/doi: 10.1109/ACCESS.2016.2566339

Christidis, Konstantinos, & Devetsikiotis, M. (2016). Blockchains and smart contracts for the internet of things. *Ieee Access*, *4*, 2292–2303.

Chu, Y., Huang, C., Xie, X., Tan, B., Kamal, S., & Xiong, X. (2018). Multilayer hybrid deep-learning method for waste classification and recycling. *Computational Intelligence and Neuroscience*, *2018*. https://doi.org/10.1155/2018/5060857

Corporation, A. (2015). *Data Sheet ATmega328P*. 1–294. http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-7810-Automotive-Microcontrollers-ATmega328P_Datasheet.pdf

Datta, P., Mohi, G., & Chander, J. (2018). Biomedical waste management in India: Critical appraisal. *Journal of Laboratory Physicians*, *10*(01), 006–014. https://doi.org/10.4103/jlp.jlp_89_17

Deka, K., Goswami, K., & Sagarika. (2018). IoT-Based Monitoring and Smart Planning of Urban Solid Waste Management. *Lecture Notes in Electrical Engineering*, *462*, 895–905. https://doi.org/10.1007/978-981-10-7901-6_96

Description, G. (2015). *Load Cell Sensor Data Sheet Load Cell*.

Dogo, E. M., Salami, A. F., Nwulu, N. I., & Aigbavboa, C. O. (2019). *Blockchain and Internet of Things-Based Technologies for Intelligent Water Management System*. 129–150. https://doi.org/10.1007/978-3-030-04110-6_7

Durrani, A. M. F., Rehman, A. U., Farooq, A., Meo, J. A., & Sadiq, M. T. (2019). An automated waste control management system (AWCMS) by using Arduino. *2019 International Conference on Engineering and Emerging Technologies (ICEET)*, 1–6.

Dutta, D., & Goel, S. (2017a). Applications of remote sensing and GIS in solid waste management - A review. In *Advances in Solid and Hazardous Waste Management* (pp. 133–151). Springer International Publishing. https://doi.org/10.1007/978-3-319-57076-1_7

Dutta, D., & Goel, S. (2017b). Applications of Remote Sensing and GIS in Solid Waste Management – A Review. *Advances in Solid and Hazardous Waste Management*, 133–151. https://doi.org/10.1007/978-3-319-57076-1_7

Emeakaroha, V. C., Cafferkey, N., Healy, P., & Morrison, J. P. (2015). A Cloud-Based IoT Data Gathering and Processing Platform. *Proceedings - 2015 International Conference on Future Internet of Things and Cloud, FiCloud 2015 and 2015 International Conference on Open and Big Data, OBD 2015*, 50–57. https://doi.org/10.1109/FiCloud.2015.53

Erfani, S. M. H., Danesh, S., Karrabi, S. M., & Shad, R. (2017). A novel approach to find and optimize bin locations and collection routes using a geographic information system. *Waste Management and Research*, *35*(7), 776–785. https://doi.org/10.1177/0734242X17706753

ESP8266 Wi-Fi MCU I Espressif Systems. (n.d.). Retrieved April 14, 2021, from https://www.espressif.com/en/products/socs/esp8266

Faccio, M., Persona, A., & Zanin, G. (2011). Waste collection multi objective model with real time traceability data. *Waste Management*, *31*(12), 2391–2405. https://doi.org/10.1016/j.wasman.2011.07.005

Fan, X., Zhu, M., Zhang, X., He, Q., & Rovetta, A. (2010). Solid waste collection optimization considering energy utilization for large city area. *2010 International Conference on Logistics Systems and Intelligent Management (ICLSIM)*, *3*, 1905–1909.

Farahbakhsh, A., & Forghani, M. A. (2019). Sustainable location and route planning with GIS for waste sorting centers, case study: Kerman, Iran. *Waste Management and Research*, *37*(3), 287–300. https://doi.org/10.1177/0734242X18815950

Flora, A. (2009). Towards a clean environment: A proposal on sustainable and integrated solid waste management system for universiti Kebangsaan Malaysia. *Report from*

Alam Flora.

Fraden, J. (2004). *Handbook of modern sensors: physics, designs, and applications*. Springer Science & Business Media.

França, A. S. L., Amato Neto, J., Gonçalves, R. F., & Almeida, C. M. V. B. (2020). Proposing the use of blockchain to improve the solid waste management in small municipalities. *Journal of Cleaner Production*, *244*. https://doi.org/10.1016/j.jclepro.2019.118529

Ghose, M. K., Dikshit, A. K., & Sharma, S. K. (2006a). A GIS based transportation model for solid waste disposal - A case study on Asansol municipality. *Waste Management*, *26*(11), 1287–1293. https://doi.org/10.1016/j.wasman.2005.09.022

Ghose, M. K., Dikshit, A. K., & Sharma, S. K. (2006b). A GIS based transportation model for solid waste disposal – A case study on Asansol municipality. *Waste Management*, *26*(11), 1287–1293. https://doi.org/10.1016/J.WASMAN.2005.09.022

Gopalakrishnan, P. K., Hall, J., & Behdad, S. (2021). Cost analysis and optimization of Blockchain-based solid waste management traceability system. *Waste Management*, *120*(xxxx), 594–607. https://doi.org/10.1016/j.wasman.2020.10.027

Gopalakrishnan, P. K., Hall, J., & Behdad, S. (2020). A Blockchain-Based Traceability System for Waste Management in Smart Cities. *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, *83952*, V006T06A015.

Gopalakrishnan, P., & Ramaguru, R. (2019). Blockchain based waste management. *International Journal of Engineering and Advanced Technology*, *8*(5), 2632–2635.

Guerrero, L. A., Maas, G., & Hogland, W. (2013). Solid waste management challenges for cities in developing countries. *Waste Management*, *33*(1), 220–232.

Gundupalli, S. P., Hait, S., & Thakur, A. (2017). A review on automated sorting of source-separated municipal solid waste for recycling. In *Waste Management* (Vol. 60, pp. 56–74). Elsevier Ltd. https://doi.org/10.1016/j.wasman.2016.09.015

Hannan, M. A., Abdulla Al Mamun, M., Hussain, A., Basri, H., & Begum, R. A. (2015a). A review on technologies and their usage in solid waste monitoring and management systems: Issues and challenges. *Waste Management*, *43*, 509–523. https://doi.org/10.1016/j.wasman.2015.05.033

Hannan, M. A., Abdulla Al Mamun, M., Hussain, A., Basri, H., & Begum, R. A. (2015b). A review on technologies and their usage in solid waste monitoring and management systems: Issues and challenges. *Waste Management*, *43*, 509–523. https://doi.org/10.1016/j.wasman.2015.05.033

Hannan, M. A., Akhtar, M., Begum, R. A., Basri, H., Hussain, A., & Scavino, E. (2018). Capacitated vehicle-routing problem model for scheduled solid waste collection and route optimization using PSO algorithm. *Waste Management*, *71*, 31–41. https://doi.org/10.1016/j.wasman.2017.10.019

Hannan, M. A., Arebey, M., Begum, R. A., & Basri, H. (2011). Radio Frequency Identification (RFID) and communication technologies for solid waste bin and truck monitoring system. *Waste Management*, *31*(12), 2406–2413. https://doi.org/10.1016/j.wasman.2011.07.022

Hannan, M. A., Arebey, M., Begum, R. A., & Basri, H. (2012). An automated solid waste bin level detection system using a gray level aura matrix. *Waste Management*, *32*(12), 2229–2238. https://doi.org/10.1016/j.wasman.2012.06.002

Hannan, M. A., Arebey, M., Begum, R. A., Basri, H., & Al Mamun, M. A. (2016). Content-based image retrieval system for solid waste bin level detection and performance evaluation. *Waste Management*, *50*, 10–19. https://doi.org/10.1016/j.wasman.2016.01.046

Home | FLoRa - A Framework for LoRa simulations. (n.d.). Retrieved February 18, 2021, from https://flora.aalto.fi/

Hong, I., Park, S., Lee, B., Lee, J., Jeong, D., & Park, S. (2014). IoT-Based Smart Garbage System for Efficient Food Waste Management. *Scientific World Journal*, *2014*. https://doi.org/10.1155/2014/646953

How Can India's Waste Problem See a Systemic Change? | Economic and Political Weekly. (n.d.). Retrieved October 23, 2020, from https://www.epw.in/engage/article/institutional-framework-implementing-solid-waste-management-india-macro-analysis

Hoy, M. B. (2017). An Introduction to the Blockchain and Its Implications for Libraries and Medicine. *Medical Reference Services Quarterly*, *36*(3), 273–279. https://doi.org/10.1080/02763869.2017.1332261

Huang, J., Pretz, T., & Bian, Z. (2010). Intelligent solid waste processing using optical sensor based sorting technology. *2010 3rd International Congress on Image and Signal Processing*, *4*, 1657–1661.

Huang, X., Xu, C., Wang, P., & Liu, H. (2018). LNSC: A Security Model for Electric Vehicle and Charging Pile Management Based on Blockchain Ecosystem. *IEEE Access*, *6*(c), 13565–13574. https://doi.org/10.1109/ACCESS.2018.2812176

Hussain, A., Draz, U., Ali, T., Tariq, S., Irfan, M., Glowacz, A., Daviu, J. A. A., Yasin, S., & Rahman, S. (2020). Waste management and prediction of air pollutants using IoT and machine learning approach. *Energies*, *13*(15). https://doi.org/10.3390/en13153930

Imran, Ahmad, S., & Kim, D. H. (2020). Quantum GIS Based Descriptive and Predictive Data Analysis for Effective Planning of Waste Management. *IEEE Access*, *8*, 46193–46205. https://doi.org/10.1109/ACCESS.2020.2979015

Indexed, S., Yerraboina, S., Kumar, N. M., Parimala, K. S., & Jyothi, N. A. (2018). *Monitoring the Smart Garbage Bin Filling Status : an Iot Application*. *9*(6), 373–381.

Jawad, H. M., Nordin, R., Gharghan, S. K., Jawad, A. M., & Ismail, M. (2017). Energy-efficient wireless sensor networks for precision agriculture: A review. *Sensors*, *17*(8), 1781.

Jensen, J. R., & Christensen, E. J. (1986). Solid and hazardous waste disposal site selection using digital geographic information system techniques. *Science of The Total Environment*, *56*, 265–276. https://doi.org/https://doi.org/10.1016/0048-9697(86)90331-1

Jinila, Y. B., Alam, M. S., & Singh, P. D. (2019). Cloud-Based Scheme for Household Garbage Collection in Urban Areas. In *Advances in Big Data and Cloud Computing* (pp. 539–546). Springer.

Jo, B. W., Khan, R. M. A., & Lee, Y. S. (2018). Hybrid blockchain and internet-of-things network for underground structure health monitoring. *Sensors (Switzerland)*, *18*(12). https://doi.org/10.3390/s18124268

Johansson, O. M. (2006). The effect of dynamic scheduling and routing in a solid waste management system. *Waste Management*, *26*(8), 875–885.

Kariapper, R. K. A. R., Pirapuraj, P., Suhail Razeeth, M. S., Nafrees, A. C. M., & Rameez, K. L. M. (2019, December 1). Smart Garbage Collection Using GPS Shortest Path Algorithm. *2019 IEEE Pune Section International Conference, PuneCon 2019*. https://doi.org/10.1109/PuneCon46936.2019.9105674

Karimi, H., Amiri, S., Huang, J., & Karimi, A. (2019). Integrating GIS and multi-criteria decision analysis for landfill site selection, case study: Javanrood County in Iran. *International Journal of Environmental Science and Technology*, *16*(11), 7305–7318. https://doi.org/10.1007/s13762-018-2151-7

Karsauliya, S. (2013). Application of Remote Sensing and GIS in Solid Waste Management: A Case Study of Surroundings of River Yamuna, India. *International Journal of Environmental Engineering and Management*, *4*(6), 2231–1319. http://www.ripublication.com/

Karthikeyan, S., Rani, G. S., Sridevi, M., & Bhuvaneswari, P. T. V. (2017). IoT enabled waste management system using ZigBee network. *2017 2nd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*, 2182–2187.

Kawai, K., & Huong, L. T. M. (2017). Key parameters for behaviour related to source separation of household organic waste: A case study in Hanoi, Vietnam. *Waste Management and Research*, *35*(3), 246–252. https://doi.org/10.1177/0734242X16683441

Khan, D., & Samadder, S. R. (2016). Allocation of solid waste collection bins and route optimisation using geographical information system: A case study of Dhanbad City, India. *Waste Management and Research*, *34*(7), 666–676. https://doi.org/10.1177/0734242X16649679

Khan, F. I., & Gawade, A. (2018). Dynamic Routing for Waste Management using IoT for Cost-Efficient Service. *International Conference on Current Trends in Computer, Electrical, Electronics and Communication, CTCEEC 2017*, 222–230. https://doi.org/10.1109/CTCEEC.2017.8455167

Kumar, S., Smith, S. R., Fowler, G., Velis, C., Kumar, S. J., Arya, S., Rena, Kumar, R., & Cheeseman, C. (2017a). Challenges and opportunities associated with waste management in India. *Royal Society Open Science*, *4*(3). https://doi.org/10.1098/rsos.160764

Kumar, S., Smith, S. R., Fowler, G., Velis, C., Kumar, S. J., Arya, S., Rena, Kumar, R., & Cheeseman, C. (2017b). Challenges and opportunities associated with waste management in India. In *Royal Society Open Science* (Vol. 4, Issue 3). Royal Society. https://doi.org/10.1098/rsos.160764

Lamichhane, M. (2017). *A smart waste management system using IoT and blockchain technology*.

Lata, K., & Singh, S. S. K. (2016). IOT based smart waste management system using Wireless Sensor Network and Embedded Linux Board. *Int. J. Curr. Trends Eng. Res*, *2*(7), 210–214.

Lavric, A., Petrariu, A. I., Coca, E., & Popa, V. (2020). Lora traffic generator based on software defined radio technology for lora modulation orthogonality analysis: Empirical and experimental evaluation. *Sensors (Switzerland)*, *20*(15), 1–19. https://doi.org/10.3390/s20154123

Lee, H. C., & Ke, K. H. (2018). Monitoring of Large-Area IoT Sensors Using a LoRa Wireless Mesh Network System: Design and Evaluation. *IEEE Transactions on Instrumentation and Measurement*, *67*(9), 2177–2187. https://doi.org/10.1109/TIM.2018.2814082

Lee, J. A., & Thomas, V. M. (2004). GPS and radio tracking of end-of-life products [recycling and waste disposal applications]. *IEEE International Symposium on Electronics and the Environment, 2004. Conference Record. 2004*, 309–312.

Leng, K., Bi, Y., Jing, L., Fu, H. C., & Van Nieuwenhuyse, I. (2018). Research on agricultural supply chain system with double chain architecture based on blockchain technology. *Future Generation Computer Systems*, *86*, 641–649. https://doi.org/10.1016/j.future.2018.04.061

Li, H., Zhu, L., Shen, M., Gao, F., Tao, X., & Liu, S. (2018). Blockchain-Based Data Preservation System for Medical Data. *Journal of Medical Systems*, *42*(8), 1–13. https://doi.org/10.1007/s10916-018-0997-3

Li, Z., Wang, W. M., Liu, G., Liu, L., He, J., & Huang, G. Q. (2017). Toward open manufacturing. *Industrial Management & Data Systems*, *118*(1), 303–320. https://doi.org/10.1108/imds-04-2017-0142

Lin, J., Yu, W., Zhang, N., Yang, X., Zhang, H., & Zhao, W. (2017). A Survey on Internet of Things: Architecture, Enabling Technologies, Security and Privacy, and Applications. *IEEE Internet of Things Journal*, *4*(5), 1125–1142. https://doi.org/10.1109/JIOT.2017.2683200

Lin, Q., Wang, H., Pei, X., & Wang, J. (2019). Food safety traceability system based on blockchain and EPCIS. *IEEE Access*, *7*, 20698–20707.

Lin, Y.-P., Petway, J., Anthony, J., Mukhtar, H., Liao, S.-W., Chou, C.-F., & Ho, Y.-F. (2017). Blockchain: The Evolutionary Next Step for ICT E-Agriculture. *Environments*, *4*(3), 50. https://doi.org/10.3390/environments4030050

Lin, Y.-P., Petway, J., Lien, W.-Y., & Settele, J. (2018). Blockchain with Artificial Intelligence to Efficiently Manage Water Use under Climate Change. *Environments*, *5*(3), 34. https://doi.org/10.3390/environments5030034

Liu, Y., Fung, K.-C., Ding, W., Guo, H., Qu, T., & Xiao, C. (2018). Novel Smart Waste Sorting System based on Image Processing Algorithms: SURF-BoW and Multi-class SVM. *Computer and Information Science*, *11*(3), 35–49.

Lokhande, P., & Pawar, M. D. (2016). Garbage Collection Management System. *Int. J. Eng. Comput. Sci*, *5*, 18800–18805.

Lotfi, S., Habibi, K., & Koohsari, M. J. (2007). Integrating GIS and fuzzy logic for urban solid waste management (a case study of Sanandaj city, Iran). *Pakistan Journal of Biological Sciences: PJBS*, *10*(22), 4000–4007.

Lozano, Á., Caridad, J., De Paz, J. F., González, G. V., & Bajo, J. (2018). Smart waste collection system with low consumption LoRaWAN nodes and route optimization. *Sensors (Switzerland)*, *18*(5), 1–24. https://doi.org/10.3390/s18051465

Lozano, Á., Caridad, J., De Paz, J. F., Villarrubia Gonzalez, G., & Bajo, J. (2018). Smart waste collection system with low consumption LoRaWAN nodes and route optimization. *Sensors*, *18*(5), 1465.

Lu, J.-W., Chang, N.-B., & Liao, L. (2013). Environmental informatics for solid and hazardous waste management: advances, challenges, and perspectives. *Critical Reviews in Environmental Science and Technology*, *43*(15), 1557–1656.

Lu, J. W., Chang, N. Bin, & Liao, L. (2013). Environmental informatics for solid and hazardous waste management: Advances, challenges, and perspectives. *Critical Reviews in Environmental Science and Technology*, *43*(15), 1557–1656. https://doi.org/10.1080/10643389.2012.671097

Lyshevski, S. E. (2018). *MEMS and NEMS: systems, devices, and structures*. CRC press.

Madakam, S., Ramaswamy, R., & Tripathi, S. (2015). Internet of Things (IoT): A Literature Review. *Journal of Computer and Communications*, *03*(05), 164–173. https://doi.org/10.4236/jcc.2015.35021

Maksimovic, M. (2018). Leveraging internet of things to revolutionize waste management. *International Journal of Agricultural and Environmental Information Systems*, *9*(4), 1–13. https://doi.org/10.4018/IJAEIS.2018100101

Marques, P., Manfroi, D., Deitos, E., Cegoni, J., Castilhos, R., Rochol, J., Pignaton, E., & Kunst, R. (2019). An IoT-based smart cities infrastructure architecture applied to a waste management scenario. *Ad Hoc Networks*, *87*, 200–208. https://doi.org/10.1016/j.adhoc.2018.12.009

McLeod, F., Erdogan, G., Cherrett, T., Bektas, T., Davies, N., Speed, C., Dickinson, J., & Norgate, S. (2013a). Dynamic collection scheduling using remote asset monitoring: Case study in the UK charity sector. *Transportation Research Record*, *2378*(1), 65–72.

McLeod, F., Erdogan, G., Cherrett, T., Bektas, T., Davies, N., Speed, C., Dickinson, J., &

Norgate, S. (2013b). Dynamic Collection Scheduling Using Remote Asset Monitoring. *Transportation Research Record: Journal of the Transportation Research Board*, *2378*(1), 65–72. https://doi.org/10.3141/2378-07

Mekki, K., Bajic, E., Chaxel, F., & Meyer, F. (2019). A comparative study of LPWAN technologies for large-scale IoT deployment. *ICT Express*, *5*(1), 1–7. https://doi.org/10.1016/j.icte.2017.12.005

Memon, S. K., Karim Shaikh, F., Mahoto, N. A., & Aziz Memon, A. (2019). IoT based smart garbage monitoring collection system using WeMos Ultrasonic sensors. *2019 2nd International Conference on Computing, Mathematics and Engineering Technologies, ICoMET 2019*, 1–6. https://doi.org/10.1109/ICOMET.2019.8673526

Memon, S. K., Shaikh, F. K., Mahoto, N. A., & Memon, A. A. (2019). IoT based smart garbage monitoring & collection system using WeMos & Ultrasonic sensors. *2019 2nd International Conference on Computing, Mathematics and Engineering Technologies (ICoMET)*, 1–6.

Mengelkamp, E., Gärttner, J., Rock, K., Kessler, S., Orsini, L., & Weinhardt, C. (2018). Designing microgrid energy markets: A case study: The Brooklyn Microgrid. *Applied Energy*, *210*, 870–880. https://doi.org/10.1016/j.apenergy.2017.06.054

Mengelkamp, E., Notheisen, B., Beer, C., Dauer, D., & Weinhardt, C. (2018). A blockchain-based smart grid: towards sustainable local energy markets. *Computer Science - Research and Development*, *33*(1–2), 207–214. https://doi.org/10.1007/s00450-017-0360-9

Milla, K., Lorenzo, A., extension, C. B.-J. of, & 2005, undefined. (n.d.). GIS, GPS, and remote sensing technologies in extension services: Where to start, what to know. *Joe.Org*. Retrieved October 26, 2020, from https://www.joe.org/joe/2005june/a6.php

Misra, D., Das, G., Chakrabortty, T., & Das, D. (2018). An IoT-based waste management system monitored by cloud. *Journal of Material Cycles and Waste Management*, *20*(3), 1574–1582. https://doi.org/10.1007/s10163-018-0720-y

Monrat, A. A., Schelén, O., & Andersson, K. (2019). A survey of blockchain from the perspectives of applications, challenges, and opportunities. *IEEE Access*, *7*, 117134–

117151.

Mundhe, N., Jaybhaye, R., & Dorik, B. (2014). Assessment of Municipal Solid Waste Management of Pune City using Geospatial Tools. *International Journal of Computer Applications*, *100*(10), 24–32. https://doi.org/10.5120/17562-8184

Mussa, A., & Suryabhagavan, K. V. (2019). Solid waste dumping site selection using GIS-based multi-criteria spatial modeling: a case study in Logia town, Afar region, Ethiopia. *Geology, Ecology, and Landscapes*, 1–13. https://doi.org/10.1080/24749508.2019.1703311

Nagori, M., Jachak, R. S., & Chaudhari, P. P. (2019). A framework for segregating solid waste by employing the technique of image annotation. *2019 Second International Conference on Advanced Computational and Communication Paradigms (ICACCP)*, 1–6.

Nagpure, A. S. (2019). Assessment of quantity and composition of illegal dumped municipal solid waste (MSW) in Delhi. *Resources, Conservation and Recycling*, *141*, 54–60. https://doi.org/10.1016/j.resconrec.2018.10.012

Naheed, S., Faiza, K., Elhadj, C. G., & Anoud, B. (2021). *Blockchain smart contracts : Applications , challenges , and future trends*.

Namasudra, S. (2018). Cloud Computing: A New Era. *Journal of Fundamental & Applied Sciences*, *10*(2), 113–135. http://ezproxy.aut.ac.nz/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=129971656&site=eds-live

Narendra Kumar, G., Swamy, C., & Nagadarshini, K. N. (2014). Efficient garbage disposal management in metropolitan cities using VANETs. *Journal of Clean Energy Technologies*, *2*(3), 258–262.

Nguyen-Trong, K., Nguyen-Thi-Ngoc, A., Nguyen-Ngoc, D., & Dinh-Thi-Hai, V. (2017). Optimization of municipal solid waste transportation by integrating GIS analysis, equation-based, and agent-based model. *Waste Management*, *59*, 14–22. https://doi.org/10.1016/j.wasman.2016.10.048

Nielsen, I., Lim, M., & Nielsen, P. (2010). Optimizing supply chain waste management through the use of RFID technology. *Proceedings of 2010 IEEE International Conference on RFID-Technology and Applications, RFID-TA 2010*, 296–301. https://doi.org/10.1109/RFID-TA.2010.5529921

Nishanth, T., Prakash, M. N., & Vijith, H. (2010). Suitable site determination for urban solid waste disposal using GIS and Remote sensing techniques in Kottayam Municipality, India. *International Journal of Geomatics and Geosciences*, *1*(2), 197.

Novo, O. (2018). Blockchain Meets IoT: An Architecture for Scalable Access Management in IoT. *IEEE Internet of Things Journal*, *5*(2), 1184–1195. https://doi.org/10.1109/JIOT.2018.2812239

O’Connor, M. C. (2008). Routeware launches RFID solution for waste haulers: The system employs low-frequency RFID interrogators on trash-collection trucks to identify tagged waste and recycling containers, as well as track the recycling efforts of the residents they serve. *RFID Journal*.

OECD Glossary of Statistical Terms - Information, Communication Technology (ICT) goods Definition. (n.d.). Retrieved March 4, 2021, from https://stats.oecd.org/glossary/detail.asp?ID=6274

Okot, P., Ogao, P. J., & Abandu, J. (2019). Site selection model for urban solid waste disposal management using GIS and remote sensing: A case of Gulu Municipality. *International Journal of Environment and Waste Management*, *24*(4), 405–436. https://doi.org/10.1504/IJEWM.2019.103645

Ølnes, S., Ubacht, J., & Janssen, M. (2017). Blockchain in government: Benefits and implications of distributed ledger technology for information sharing. *Government Information Quarterly*, *34*(3), 355–364. https://doi.org/10.1016/j.giq.2017.09.007

OMNeT++ Discrete Event Simulator. (n.d.). Retrieved February 18, 2021, from https://omnetpp.org/

On, P. P. (2009). the Solid Waste Management Sector. *Economic Affairs*, *November*.

Ongena, G., Smit, K., Boksebeld, J., Adams, G., Roelofs, Y., & Ravesteijn, P. (2018). Blockchain-based Smart Contracts in Waste Management: A Silver Bullet? *Digital Transformation – Meeting the Challenges*, 345–356. https://doi.org/10.18690/978-

961-286-170-4.23

Ortín, J., Cesana, M., & Redondi, A. (2018). How do ALOHA and listen before talk coexist in LoRaWAN? *2018 IEEE 29th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 1–7.

Ouaddah, A., Abou Elkalam, A., & Ait Ouahman, A. (2016). FairAccess: a new Blockchain-based access control framework for the Internet of Things. *Security and Communication Networks*, *9*(18), 5943–5964.

Petajajarvi, J., Mikhaylov, K., Roivainen, A., Hanninen, T., & Pettissalo, M. (2015). On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology. *2015 14th International Conference on ITS Telecommunications (ITST)*, 55–59.

Pflanzner, Tamas, & Kertész, A. (2016). A survey of IoT cloud providers. *2016 39th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, 730–735.

Pflanzner, Tamás, & Kertész, A. (2018). A taxonomy and survey of IoT cloud applications. *EAI Endorsed Transactions on Internet of Things*, *3*(12), Terjedelem-14.

Planning Commission Report. (2014). Reports of the taskforce on waste to energy (Vol-I) (Retrieved from http://planningcommission.nic.in/reports/genrep/rep_wte1205.pdf - Google Search. (n.d.). Retrieved October 23, 2020, from https://www.google.com/search?sxsrf=ALeKk02gzAi-UKnfoNBInfsqjQX6mWBj8g%3A1603450870682&ei=9reSX5mOKZHf9QO2vLLgDw&q=+Planning+Commission+Report.+%282014%29.+Reports+of+the+taskforce+on+waste+to+energy+%28Vol-I%29+%28Retrieved+from+http%3A%2F%2Fplanningcomm

Pop, C., Cioara, T., Antal, M., Anghel, I., Salomie, I., & Bertoncini, M. (2018). Blockchain based decentralized management of demand response programs in smart energy grids. *Sensors (Switzerland)*, *18*(1). https://doi.org/10.3390/s18010162

Popa, C. L., Carutasu, G., Cotet, C. E., Carutasu, N. L., & Dobrescu, T. (2017). Smart city platform development for an automated waste collection system. *Sustainability*

(Switzerland), *9*(11), 1–15. https://doi.org/10.3390/su9112064

Postman API Platform | Sign Up for Free. (n.d.). Retrieved March 7, 2022, from https://www.postman.com/

Rad, M. S., von Kaenel, A., Droux, A., Tieche, F., Ouerhani, N., Ekenel, H. K., & Thiran, J.-P. (2017). A computer vision system to localize and classify wastes on the streets. *International Conference on Computer Vision Systems*, 195–204.

Rahman, M. W., Islam, R., Hasan, A., Bithi, N. I., Hasan, M. M., & Rahman, M. M. (2020). Intelligent waste management system using deep learning with IoT. *Journal of King Saud University-Computer and Information Sciences*.

Rajendran, K., Björk, H., & Taherzadeh, M. J. (2013). Borås, a zero waste city in Sweden. *Journal of Development Management*, *1*(1), 3–8.

Ramachandra, T. V., Bharath, H. A., Kulkarni, G., & Han, S. S. (2018). Municipal solid waste: Generation, composition and GHG emissions in Bangalore, India. In *Renewable and Sustainable Energy Reviews* (Vol. 82, pp. 1122–1136). Elsevier Ltd. https://doi.org/10.1016/j.rser.2017.09.085

Rathore, P., Sarmah, S. P., & Singh, A. (2020). Location–allocation of bins in urban solid waste management: a case study of Bilaspur city, India. *Environment, Development and Sustainability*, *22*(4), 3309–3331. https://doi.org/10.1007/s10668-019-00347-y

Ray, P. P. (2016). A survey of IoT cloud platforms. *Future Computing and Informatics Journal*, *1*(1–2), 35–46. https://doi.org/10.1016/J.FCIJ.2017.02.001

Reis, P., Caetano, F., Pitarma, R., & Gonçalves, C. (2015). IEcoSys – an intelligent waste management system. *Advances in Intelligent Systems and Computing*, *353*, 843–853. https://doi.org/10.1007/978-3-319-16486-1_84

Remote Sensing: Models and Methods for Image Processing - Robert A. Schowengerdt - Google Books. (n.d.). Retrieved October 26, 2020, from https://books.google.co.in/books?hl=en&lr=&id=KQXNaDH0X-IC&oi=fnd&pg=PP1&ots=sogWMLD9KG&sig=fUMALhqfpyKRDk3e5PgN6WhA7rQ&redir_esc=y#v=onepage&q&f=false

Richter, A., Ng, K. T. W., & Karimi, N. (2019). A data driven technique applying GIS, and remote sensing to rank locations for waste disposal site expansion. *Resources, Conservation and Recycling*, *149*, 352–362. https://doi.org/10.1016/j.resconrec.2019.06.013

Roehrs, A., da Costa, C. A., da Rosa Righi, R., da Silva, V. F., Goldim, J. R., & Schmidt, D. C. (2019). Analyzing the performance of a blockchain-based personal health record implementation. *Journal of Biomedical Informatics*, *92*, 103140. https://doi.org/10.1016/j.jbi.2019.103140

Rovetta, A., Xiumin, F., Vicentini, F., Minghua, Z., Giusti, A., & Qichang, H. (2009). Early detection and evaluation of waste through sensorized containers for a collection monitoring application. *Waste Management*, *29*(12), 2939–2949. https://doi.org/10.1016/j.wasman.2009.08.016

Rybnytska, O., Burstein, F., Rybin, A. V., & Zaslavsky, A. (2018). Decision support for optimizing waste management. *Journal of Decision Systems*, *27*, 67–78. https://doi.org/10.1080/12460125.2018.1464312

Saari, M., bin Baharudin, A. M., Sillberg, P., Hyrynsalmi, S., & Yan, W. (2018). LoRa—A survey of recent research trends. *2018 41st International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, 872–877.

Saleh, H. E.-D. M. (2016). Introductory Chapter: Introduction to Hazardous Waste Management. In *Management of Hazardous Wastes*. InTech. https://doi.org/10.5772/64245

Satria, D., & Hidayat, T. (2019). Implementation of wireless sensor network (WSN) on garbage transport warning information system using GSM module. *Journal of Physics: Conference Series*, *1175*(1), 12054.

Semtech Corporation. (2016). *SX1276/77/78/79 - 137 MHz to 1020 MHz Low Power Long Range Transceiver*. *August*, 133.

Sethi, P., & Sarangi, S. R. (2017). Internet of Things: Architectures, Protocols, and Applications. In *Journal of Electrical and Computer Engineering* (Vol. 2017). Hindawi Publishing Corporation. https://doi.org/10.1155/2017/9324035

Sharma, N., Litoriya, R., & Sharma, D. (n.d.). *Forecasting the Most Predictable Municipal Solid Wastes for Improving the Quality of Waste Management System in Urban & Rural Areas of India*.

Sharma, P. K., & Park, J. H. (2018a). Blockchain based hybrid network architecture for the smart city. *Future Generation Computer Systems*, *86*, 650–655.

Sharma, P. K., & Park, J. H. (2018b). Blockchain based hybrid network architecture for the smart city. *Future Generation Computer Systems*, *86*, 650–655. https://doi.org/10.1016/j.future.2018.04.060

Sheng, T. J., Islam, M. S., Misran, N., Baharuddin, M. H., Arshad, H., Islam, M. R., Chowdhury, M. E. H., Rmili, H., & Islam, M. T. (2020). An Internet of Things Based Smart Waste Management System Using LoRa and Tensorflow Deep Learning Model. *IEEE Access*, *8*, 148793–148811. https://doi.org/10.1109/ACCESS.2020.3016255

Shirke, P. S. I., Ithape, S., Lungase, S., & Mohare, M. (2019). *Automation of smart waste management using IoT*. *June*, 414–419.

Singh, A. (2012). An overview of the optimization modelling applications. *Journal of Hydrology*, *466*, 167–182.

Singh, A. (2019). Remote sensing and GIS applications for municipal waste management. *Journal of Environmental Management*, *243*, 22–29. https://doi.org/10.1016/j.jenvman.2019.05.017

Singhvi, R. K., Lohar, R. L., Kumar, A., Sharma, R., Sharma, L. D., & Saraswat, R. K. (2019, April 1). IoT BasedSmart Waste Management System: India prospective. *Proceedings - 2019 4th International Conference on Internet of Things: Smart Innovation and Usages, IoT-SIU 2019*. https://doi.org/10.1109/IoT-SIU.2019.8777698

Sinha, R. S., Wei, Y., & Hwang, S.-H. (2017). A survey on LPWA technology: LoRa and NB-IoT. *Ict Express*, *3*(1), 14–21.

Slabicki, M., Premsankar, G., & Di Francesco, M. (2018). Adaptive configuration of LoRa networks for dense IoT deployments. *NOMS 2018-2018 IEEE/IFIP Network*

Operations and Management Symposium, 1–9.

Soh, Z. H. C., Husa, M. A. A.-H., Abdullah, S. A. C., & Shafie, M. A. (2019). Smart Waste Collection Monitoring and Alert System via IoT. *2019 IEEE 9th Symposium on Computer Applications & Industrial Electronics (ISCAIE)*, 50–54.

Sohag, M. U., & Podder, A. K. (2020). Smart garbage management system for a sustainable urban life: An IoT based application. *Internet of Things*, *11*, 100255.

Solano Meza, J. K., Rodrigo-Ilarri, J., Romero Hernández, C. P., & Rodrigo-Clavero, M. E. (2020). Analytical Methodology for the Identification of Critical Zones on the Generation of Solid Waste in Large Urban Areas. *International Journal of Environmental Research and Public Health*, *17*(4), 1196. https://doi.org/10.3390/ijerph17041196

'Solid Waste Management Rules Revised After 16 Years; Rules Now Extend to Urban and Industrial Areas': Javadekar. (n.d.). Retrieved August 11, 2021, from https://pib.gov.in/newsite/PrintRelease.aspx?relid=138591

Srivastava, V., Ismail, S. A., Singh, P., & Singh, R. P. (2015). Urban solid waste management in the developing world with emphasis on India: challenges and opportunities. *Reviews in Environmental Science and Biotechnology*, *14*(2), 317–337. https://doi.org/10.1007/s11157-014-9352-4

Steyn, L. J., & Willemse, E. J. (2018, September 13). Using Vehicle GPS Data to Infer Offloading Times of Waste Collection Vehicles at Transfer Stations. *2018 International Conference on Advances in Big Data, Computing and Data Communication Systems, IcABCD 2018*. https://doi.org/10.1109/ICABCD.2018.8465472

Su, Z., Wang, Y., Xu, Q., Fei, M., Tian, Y. C., & Zhang, N. (2018). A Secure Charging Scheme for Electric Vehicles with Smart Communities in Energy Blockchain. *IEEE Internet of Things Journal*, *4662*(c), 1–14. https://doi.org/10.1109/JIOT.2018.2869297

Sundas, A., & Panda, S. N. (2020). IoT Based Integrated Technologies for Garbage Monitoring System. *2020 8th International Conference on Reliability, Infocom*

Technologies and Optimization (Trends and Future Directions)(ICRITO), 57–62.

Suryawanshi, S., Bhuse, R., Gite, M., & Hande, D. (2018). Waste Management System Based On IoT. *International Research Journal of Engineering and Technology*, 1835–1837. www.irjet.net

Szoke-sieswerda, J. M., & Szoke-sieswerda, J. M. (2014). *A Vision System for Automating Municipal Waste Collection*. *September*.

Tarone, Katgube, A. A., Shendre, H. H., Ghugal, R. P., & Bobade, P. N. P. (2018). IOT Based Smart Garbage Monitoring System Using ESP8266 with GPS Link. *International Research Journal of Engineering and Technology (IRJET)*, *05*(03), 5–6.

Tavares, G., Zsigraiova, Z., Semiao, V., & Carvalho, M. G. (2009). Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling. *Waste Management*, *29*(3), 1176–1185. https://doi.org/10.1016/j.wasman.2008.07.013

Thanawala, D., Sarin, A., & Verma, P. (2020). An Approach to Waste Segregation and Management Using Convolutional Neural Networks. *International Conference on Advances in Computing and Data Sciences*, 139–150.

THE 17 GOALS | Sustainable Development. (n.d.). Retrieved March 15, 2021, from https://sdgs.un.org/goals

The Weight of Cities | Resource Panel. (n.d.). Retrieved August 10, 2021, from https://www.resourcepanel.org/reports/weight-cities

Town, B., Asefa, B., & Mindahun, W. (2020). Suitable Solid Waste Disposal Site Selection Using Geographical Information System: A Case of Debre Markos Town, Ethiopia. *Journal of Environment and Earth Science*, *7*(1), 17–23. https://doi.org/10.7176/jees/10-8-03

Tsai, F. M., Bui, T. D., Tseng, M. L., Lim, M. K., & Hu, J. (2020). Municipal solid waste management in a circular economy: A data-driven bibliometric analysis. *Journal of Cleaner Production*, *275*, 124132. https://doi.org/10.1016/j.jclepro.2020.124132

Tseng, J. H., Liao, Y. C., Chong, B., & Liao, S. W. (2018). Governance on the drug supply chain via gcoin blockchain. *International Journal of Environmental Research and*

Public Health, *15*(6). https://doi.org/10.3390/ijerph15061055

Vambol, S., Vambol, V., Sundararajan, M., & Ansari, I. (2019). The nature and detection of unauthorized waste dump sites using remote sensing. *Ecological Questions*, *30*(3), 43–55. https://doi.org/10.12775/EQ.2019.018

Vasagade, T. S., Tamboli, S. S., & Shinde, A. D. (2020). Smart Solid Waste Collection and Management System. In *Techno-Societal 2018* (pp. 663–671). Springer International Publishing. https://doi.org/10.1007/978-3-030-16848-3_61

Vijay, R., Gautam, A., Kalamdhad, A., Gupta, A., & Devotta, S. (2008). GIS-based locational analysis of collection bins in municipal solid waste management systems. *Journal of Environmental Engineering and Science*, *7*(1), 39–43.

Visual Studio Code - Code Editing. Redefined. (n.d.). Retrieved March 7, 2022, from https://code.visualstudio.com/

Vo, A. H., Vo, M. T., & Le, T. (2019). A novel framework for trash classification using deep transfer learning. *IEEE Access*, *7*, 178631–178639.

Voltage, S., Current, S., & Format, O. D. (n.d.). *Ultrasonic Distance Sensor - Serial Out [1166] : Sunrom Electronics/Technologies*. https://www.sunrom.com/p/ultrasonic-distance-sensor-serial-out

Vu, H. L., Bolingbroke, D., Ng, K. T. W., & Fallah, B. (2019). Assessment of waste characteristics and their impact on GIS vehicle collection route optimization using ANN waste forecasts. *Waste Management*, *88*, 118–130. https://doi.org/10.1016/j.wasman.2019.03.037

Vu, H. L., Ng, K. T. W., & Bolingbroke, D. (2018). Parameter interrelationships in a dual phase GIS-based municipal solid waste collection model. *Waste Management*, *78*, 258–270. https://doi.org/10.1016/j.wasman.2018.05.050

Vu, H. L., Ng, K. T. W., Fallah, B., Richter, A., & Kabir, G. (2020). Interactions of residential waste composition and collection truck compartment design on GIS route optimization. *Waste Management*, *102*, 613–623. https://doi.org/10.1016/j.wasman.2019.11.028

Wagland, S. T., Veltre, F., & Longhurst, P. J. (2012). Development of an image-based analysis method to determine the physical composition of a mixed waste material. *Waste Management*, *32*(2), 245–248.

Wang, J., Wang, Q., Zhou, N., & Chi, Y. (2017). A novel electricity transaction mode of microgrids based on blockchain and continuous double auction. *Energies*, *10*(12), 1–22. https://doi.org/10.3390/en10121971

Weber, M., Lučić, D., & Lovrek, I. (2017). Internet of Things context of the smart city. *2017 International Conference on Smart Systems and Technologies (SST)*, 187–193.

Welcome to Flask — Flask Documentation (2.0.x). (n.d.). Retrieved May 19, 2021, from https://flask.palletsprojects.com/en/2.0.x/

Wilson, B. G., & Vincent, J. K. (2008). Estimating waste transfer station delays using GPS. *Waste Management*, *28*(10), 1742–1750. https://doi.org/10.1016/j.wasman.2007.09.020

Wilson, S. T., Sebastine, T. K., Daniel, M., & Martin, V. (2019). *Smart trash bin for waste management using odor sensor based on IoT technology*. *5*(2), 2048–2051.

Wu, H., Li, Z., King, B., Ben Miled, Z., Wassick, J., & Tazelaar, J. (2017). A distributed ledger for supply chain physical distribution visibility. *Information*, *8*(4), 137.

Wu, J., Guo, S., Huang, H., Liu, W., & Xiang, Y. (2018). Information and communications technologies for sustainable development goals: state-of-the-art, needs and perspectives. *IEEE Communications Surveys & Tutorials*, *20*(3), 2389–2406.

Xu, Q., Aung, K. M. M., Zhu, Y., & Yong, K. L. (2018). A blockchain-based storage system for data analytics in the internet of things. In *New Advances in the Internet of Things* (pp. 119–138). Springer.

Xu, R., Chen, Y., Blasch, E., & Chen, G. (2018). BlendCAC: A Smart Contract Enabled Decentralized Capability-Based Access Control Mechanism for the IoT. *Computers*, *7*(3), 39. https://doi.org/10.3390/computers7030039

Xu, X., Pautasso, C., Gramoli, V., Ponomarev, A., & Chen, S. (n.d.). *The Blockchain as a Software Connector*.

Yang, K., Zhou, X. N., Yan, W. A., Hang, D. R., & Steinmann, P. (2008). Landfills in Jiangsu province, China, and potential threats for public health: Leachate appraisal and spatial analysis using geographic information system and remote sensing. *Waste Management*, *28*(12), 2750–2757. https://doi.org/10.1016/j.wasman.2008.01.021

Yu, Y. (2020). A Computer Vision Based Detection System for Trash Bins Identification during Trash Classification. *Journal of Physics: Conference Series*, *1617*(1), 12015.

Yun, K., Kwon, Y., Oh, S., Moon, J., & Park, J. (2019). Vision-based garbage dumping action detection for real-world surveillance platform. *ETRI Journal*, *41*(4), 494–505. https://doi.org/10.4218/etrij.2018-0520

Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of things for smart cities. *IEEE Internet of Things Journal*, *1*(1), 22–32. https://doi.org/10.1109/JIOT.2014.2306328

Zavare, S., Parashare, R., Patil, S., Rathod, P., & Babanne, V. (2017). Smart City waste management system using GSM. *Int. J. Comput. Sci. Trends Technol*, *5*(3), 74–78.

Zeeshan, S., Shahid, Z., Khan, S., & Shaikh, F. A. (2018). Solid Waste Management in Korangi District of Karachi using GPS and GIS: A Case study. *2018 7th International Conference on Computer and Communication Engineering (ICCCE)*, 1–4.

Zhang, A., Zhong, R. Y., Farooque, M., Kang, K., & Venkatesh, V. G. (2020). Blockchain-based life cycle assessment: An implementation framework and system architecture. *Resources, Conservation and Recycling*, *152*(September 2019), 104512. https://doi.org/10.1016/j.resconrec.2019.104512

Ziouzios, D., & Dasygenis, M. (2019, September 1). A smart bin implementantion using LoRa. *2019 4th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference, SEEDA-CECNSM 2019*. https://doi.org/10.1109/SEEDA-CECNSM.2019.8908523