# DESIGN AND DEVELOPMENT OF A SYSTEM FOR MONITORING CRITICAL PARAMETERS OF A CRUDE OIL PIPELINE BASED ON LORA AND IOT

A Thesis

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

**DOCTOR OF PHILOSOPHY**

**in**

**Electronics & Communication Engineering**

**By**

**Lakshmi Narayana Chavala**
**Registration No: 41800551**

**Supervised By**

**Dr. Rajesh Singh**
**Professor**
**School of Electronics &**
**Electrical Engineering**

**Co-Supervised by**

**Dr. Anita Gehlot**
**Associate Professor**
**School of Electronics &**
**Electrical Engineering**

**LOVELY PROFESSIONAL UNIVERSITY**
**PUNJAB**
**January 2022**

# DECLARATION

This thesis is an account of research undertaken between August 2018 and January 2022 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.

Lakshmi Narayana Chavala

Registration No: 41800551

School of Electronics & Electrical Engineering

Lovely Professional University, Punjab

# 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 a System for Monitoring Critical Parameters of a Crude oil Pipeline Based on LoRa and IoT**" 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.


Dr. Rajesh Singh, Professor
School of Electronics & Electrical Engineering,
Lovely Professional University, Punjab

Dr. Anita Gehlot, Associate Professor
School of Electronics & Electrical Engineering,
Lovely Professional University, Punjab

# ABSTRACT

The oil industry is one of the world's eight essential industries, and it has a significant impact on how other critical sectors of the economy make decisions. Because the world's economic growth is strongly linked to its energy demand, the oil demand is expected to increase, making the sector attractive for investment. The oil business involves industrial processes, which are carried out in three sectors: upstream, midstream, and downstream. The upstream segment is in process of finding and exploiting raw materials. The midstream is responsible for transporting oil to various locations for storage through pipelines, oil tankers, rail etc. Process in downstream is refining of oil and finally, distributing in the market through petrol stations. Petrol, diesel, lubricants, and other final products are created to market and distribute. Here in the midstream sector transportation oil through pipelines has several advantages, including safety, stability, cost savings, and increased efficiency. Pipelines that aren't adequately maintained and could cause major problems have a severe impact on both the natural and human environment. Because of the growing need for system availability, a scarcity of human resources, and cost constraints, effective maintenance practices have become more important. Various standards and technologies are already vying for control over the Internet of Things, with a focus on remote sensing and computing. One of these technologies that are gaining attraction in the application of IoT is LoRa. LoRa has a significant advantage over its competitors due to its ability to create communication linkages over long distances with very simple nodes, minimum infrastructure, use of license-free ISM bands and minimal power requirements.

This thesis presents a solution for oil pipeline maintenance combining the IoT and LoRa communication technologies to solve critical difficulties of oil pipeline monitoring. For oil pipeline monitoring remotely, we propose solar-powered hybrid architecture based on LoRa and Zigbee communication protocol. In addition, customized sensor nodes, and a gateway are designed and installed to monitor critical parameters of the oil pipeline such as oil temperature, pressure, flow check, vibrations, and acoustic waves of the oil pipeline. Here we have incorporated Zigbee for short-distance communication to activate safety operation controller

(SOC) and unmanned aerial vehicle (UAV) which is used for pipeline inspection for on-demand visual collection of the pipeline. We analyzed various parameters of Zigbee communication protocol like throughput, end to end delay, packet delivery ratio (PDR), retransmission attempts, queue size and queuing delay using OPNET simulator. The LoRa protocol is used for long-distance data transmission to deliver real-time pipeline monitoring data to the end-user. Spreading facto (SF), Bandwidth (BW), Code rate (CR), bit rate, link budget, RSSI, SNR, and sensitivity are among the LoRa assessment measures examined. Further the establishment of long-range network in between the sensor node and gateway is processed for data transmission and stored data in IoT cloud server through Wireless Fidelity (Wi-Fi). The experimental results show promising scope towards a precise, low complex system that monitors the health of the oil pipeline.

# DEDICATION

"*This Thesis Work Truly and Heart fully Dedicated to My Parents for their Inspiration and Motivation Behind My Success*"

# 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 Baz, Mamoon Rashid, Sultan S. Alshamrani and Deepak Prashar for their valuable suggestions and assistance in my 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: 06/01/2022 Lakshmi Narayana Chavala

# CONTENTS


Declaration ........................................................................ i
Certificate ........................................................................ ii
Abstract ........................................................................ iii
Dedication ........................................................................ v
Acknowledgement ........................................................................ vi
List of Figures ........................................................................ x
List of Tables ........................................................................ xvii
List of Abbreviations ........................................................................ xix

**Chapter 1 Introduction**........................................................................ 1

1.1 Background........................................................................ 1

1.2 Oil Pipeline monitoring technologies ........................................................ 5

1.3 Communication Protocols........................................................ 7

1.4 Unmanned Aerial vehicles (UAV)........................................................ 14

1.5 Renewable Energy........................................................ 16

1.6 Research Objectives........................................................ 17

1.7 Thesis Organization........................................................ 17

1.8 Chapter Summary........................................................ 18

**Chapter 2 Review of Literature** ........................................................ 19

2.1 Review on Oil Industry........................................................ 19

2.2 Pipes and Materials........................................................ 21

2.3 Pipeline Leaks Detection and Localization Methods………………………………. 24

2.4 Wireless Sensor Networks ………………………………………………………… 29

2.5 Internet of Things (IoT)………………………………………………………….. 31

2.6 Oil Pipelines Management........................................................................................ 36

2.7 Research Gap ……………………………………………………………………… 45

2.8 Chapter Summary…………………………………………………………………... 45

**Chapter 3 System Architecture** ........................................................................................ 46

3.1 System Architecture………………………………………………………….... 46

3.2 Sensor node-1……………………………………………………………………… 47

3.3 Sensor node-2……………………………………………………………………… 53

3.4 Safety Operation controller……………………………………………………......... 68

3.5 Gateway…………………………………………………………………………….. 61

3.6 Sensor Components………………………………………………………….......... 68

3.7 Chapter Summary…………………………………………………………………... 70

**Chapter 4 Network Performance Analysis**……………………………………........... 71

4.1 OPNET simulator……………………………………………........................................ 71

4.2 Framework for LoRa network……………………………………….................... 72

4.3 Framework for Zigbee network ………………………………………….............. 83

4.4 Simulation of energy harvesting………………………………………………… 87

4.5 Chapter Summary…………………………………………………………………... 89

**Chapter 5 Unmanned Aerial Vehicle**........................................................................ 90

5.1 Introduction to Unmanned Aerial Vehicles ……………………………………….. 90

5.2 AutoCAD Design………………………………………………………………….. 91

5.3 Simulation model of quadcopter ………………………………………………... 94

5.4 Chapter Summary………………………………………..……..……............... 105

**Chapter 6 Data Analysis..........................................................................................** 106

6.1 Data acquisition.......................................................................................... 106

6.1.1 Case-I: Smooth transportation of Oil through pipeline............................. 106

6.1.2 Case-II: Third-party Damage (TPD) on the Pipeline................................ 111

6.1.3 Case-III: Leak due to Third party damage................................................ 119

6.2 Algorithm for Monitoring Oil Pipeline............................................................. 126

6.3 Power Consumption Analysis.......................................................................... 129

6.4 Chapter Summary.......................................................................................... 130

**Chapter 7 Conclusion and Future Scope..............................................................** 131

7.1 Conclusion.................................................................................................. 131

7.2 Novelty....................................................................................................... 137

7.3 Future work................................................................................................. 137

7.4 Publications................................................................................................ 138

# LIST OF FIGURES


1.1 World oil production statistics………………………………………………. 1

1.2 Oil industrial operation Sectors……………………………………………… 2

1.3 Various modes of Oil transportation………………………………………… 3

1.4 Pipeline Network of oil companies ………………………………….…..... 3

1.5 Oil spills due to Pipeline failure…………………………………………….. 4

1.6 Oil pipeline failure causes ……………………………………………….…. 4

1.7 Pipeline leakage detection methods ………………………………………… 5

1.8 Zigbee Architecture ……………………………………………………….... 8

1.9 LoRa Architecture…………………………………………………………… 10

1.10 LoRa Packet Structure……………………………………………………….. 13

1.11 UAS systems………………………………………………………………….. 15

1.12 Solar powered sensor nodes…………………………………………………. 16

2.1 Barrels of liquid spilled………………………………………………………. 20

2.2 Steeel Pipes………………………………………………………………….. 21

2.3 Steel Pipes affected by corrosion……………………………………………. 22

2.4 Thermoplastic pipes……………………………………………………......... 23

2.5 Fiber optic cable system……………………………………………………... 25

| | | |
|---|---|---|
| 2.6 | Fundamental elements of an IR thermography camera……………………… | 26 |
| 2.7 | WSN architecture …………………………………………………....... | 30 |
| 2.8 | Applications of WSN ……………………………………………………….. | 31 |
| 2.9 | Illustration of data acquisition equipment in IoT …………………………… | 32 |
| 2.10 | IoT communication technologies ……………….......................................... | 33 |
| 2.11 | Zigbee Protocol stack ……………………………………………………….. | 35 |
| 3.1 | System Architecture for pipeline parameters monitoring in Oil field………. | 47 |
| 3.2 | Block diagram of Sensor node-1…………………………………………….. | 38 |
| 3.3 | Proteus simulations of sensor node-1……………………………….......... | 38 |
| 3.4 | Circuit design of sensor node-1…………………………………….......... | 39 |
| 3.5 | PCB Layout of sensor node-1……………………………………………… | 50 |
| 3.6 | Customized hardware of sensor node-1…………………………………… | 51 |
| 3.7 | Methodology for sensor node-1…………………………………………… | 52 |
| 3.8 | Block diagram of Sensor node-2…………………………………………... | 53 |
| 3.9 | Proteus simulations of Sensor node-2……………………………………… | 54 |
| 3.10 | Circuit design of Sensor node-2…………………………………………… | 54 |
| 3.11 | PCB Layout of Sensor node-2…………………………………….......... | 55 |
| 3.12 | Customized hardware prototype of Sensor node-2………………………… | 56 |
| 3.13 | Methodology for Sensor node-2…………………………………………… | 57 |
| 3.14 | Safety operation controller device ………………………………………….. | 58 |

| | | |
|---|---|---|
| 3.15 | Proteus simulation of SOC …………………………………………………..... | 59 |
| 3.16 | Circuit design of SOC section ……………………………..…………….. | 59 |
| 3.17 | PCB layout of SOC device ……………………………..……………… | 60 |
| 3.18 | Hardware prototype of SOC device ……………………..…………..... | 61 |
| 3.19 | Gateway ………………………………………………………..……………. | 61 |
| 3.20 | Gateway Simulations with Node MCU ………………………..………. | 62 |
| 3.21 | Circuit design of Gateway ……………………………………..………. | 63 |
| 3.22 | PCB Layout of Gateway ……………………………………..…………... | 64 |
| 3.23 | Customized hardware prototype of Gateway ……………..………… | 65 |
| 3.24 | Methodology of Gateway ………………………..…………………...... | 66 |
| 3.25 | Temperature sensor…………………………..……….................... | 67 |
| 3.26 | Humidity sensor DHT11……………………………..………………… | 67 |
| 3.27 | Pressure sensor ……………………………..……………………………. | 68 |
| 3.28 | Flow rate sensor ……………………………..………………………… | 68 |
| 3.29 | Vibration sensor ………………………..…………………………………. | 68 |
| 3.30 | Sound sensor ……………………………..……………………………. | 69 |
| 3.31 | Smoke detection sensor……………………..…………………………….. | 69 |
| 4.1 | OPNET simulator ………………………..………………………………… | 72 |
| 4.2 | Framework for LoRa………………………..…………………………. | 72 |
| 4.3 | RSSI Vs Distance ……………………………..…………………………….. | 74 |

| | | |
|---|---|---|
| 4.4 | TOA vs. payload at different SF ………………………………..…………... | 75 |
| 4.5 | SNR vs Distance ……………………………..………………………… | 76 |
| 4.6 | PER Vs Payload size ……………………………..……………………. | 77 |
| 4.7 | Bit rate of SF7-SF12…………………………..……………………….. | 79 |
| 4.8 | Receiver sensitivity …………………………..…………………………….. | 80 |
| 4.9 | Link budget……………………………..………………………………. | 81 |
| 4.9 | Gateway receiving data ………………………………………………….... | 82 |
| 4.10 | Framework of Zigbee network in OPNET modeler…………………………. | 84 |
| 4.11 | Packet error Rate for 2.4GHz and 916MHz bands………………………….. | 85 |
| 4.12 | Retransmission attempts for 2.4GHz and 916MHz bands ………………….. | 85 |
| 4.13 | Throughput for 2.4GHz and 916MHz bands ……………………………….. | 86 |
| 4.14 | End to End delay for 2.4GHz and 916MHz bands ………………………..... | 87 |
| 4.15 | Sensor node energy conservation using renewable resource ……………..... | 88 |
| 5.1 | Quad copter structure …………………………………………………….. | 91 |
| 5.2 | Block diagram of quad copter …………………………………………..... | 93 |
| 5.3 | Structure dimensions …………………………………….................... | 94 |
| 5.4 | Bar displacement distribution and Displacement of Bar …………………… | 95 |
| 5.5 | Bar Stress distribution and stress of Bar ……………………………….... | 95 |
| 5.6 | Base plate displacement distribution and displacement of base plate ……… | 96 |
| 5.7 | Base plate stress distribution and stress of base plate ……………………… | 97 |

| | | |
|---|---|---|
| 5.8 | Structure displacement behavior and displacement of structure……………. | 97 |
| 5.9 | Structure Stress behavior and stress of structure ……………………........... | 98 |
| 5.10 | CAD model of quadcopter ……………………………………………………….. | 99 |
| 5.11 | Flight stabilization system ……………………………………………………….. | 99 |
| 5.12 | Electronic speed controller ……………………………………………………… | 100 |
| 5.13 | Circuit design of electronic components ……………………………………… | 100 |
| 5.14 | Electronic components of drone ………………………………………………… | 101 |
| 5.15 | Final Assembly of parts of systems …………………………………………… | 102 |
| 5.16 | Takeoff weight of drone……………………………………………………….. | 103 |
| 5.17 | Methodology of drone yard ……………………………………………………… | 104 |
| 6.1 | Temperature of Oil ……………………………………………………………… | 106 |
| 6.2 | Pressure of the pipeline ………………………………………………………... | 107 |
| 6.3 | Flow rate of oil ………………………………………………………………… | 108 |
| 6.4 | Humidity ……………………………………………………………….…..... | 109 |
| 6.5 | Received signal strength indicator ………………………………………...... | 110 |
| 6.6 | Parameters for Case-1……………………………………….......................... | 110 |
| 6.7 | Third-party damage on pipeline………………………………………........... | 111 |
| 6.8 | Acoustic signals at Level –I……………………………………….................. | 112 |
| 6.9 | Acoustic signals at Level –II………………………………........................... | 113 |
| 6.10 | Acoustic signals at Level –III……………………………………….............. | 113 |

| | | |
|---|---|---|
| 6.11 | Vibration of the pipe………………………………………......................... | 115 |
| 6.12 | Flow rate…………………………………........................................... | 116 |
| 6.13 | Pressure…………………………………........................................... | 116 |
| 6.14 | Thingspeak dashboard of Case-II………………………………………........ | 117 |
| 6.15 | Damage localization using Drone………………………………………...... | 118 |
| 6.16 | Pipe Spills due to damage……………………………………….................. | 119 |
| 6.17 | Pressure…………………………………........................................... | 120 |
| 6.18 | Flow rate…………………………………........................................... | 120 |
| 6.19 | Vibrations…………………………………......................................... | 121 |
| 6.20 | Acoustic waves…………………………………................................. | 121 |
| 6.21 | Schematic representation of detection end device placement …………….. | 121 |
| 6.22 | Cayenne dashboard……………………………………….......................... | 122 |
| 6.23 | ThingSpeak dashboard of Case-III………………………………………..... | 124 |
| 6.24 | Leak Localization Using Drone……………………………………….......... | 125 |
| 6.25 | Experimental setup………………………………………....................... | 125 |
| 6.26 | Measuring of voltage of IR proximity sensor ………………………………. | 129 |
| 6.27 | Power consumption analysis……………………………………………… | 130 |
| 7.1 | Sensor node with solar on the pipeline……………………………………… | 132 |
| 7.2 | Oil Pipeline monitoring …………………………………………………….. | 133 |
| 7.3 | Serial communication of transmission and reception of sensor node …….... | 134 |

7.4 SOC with Hooter ……………………………………………………..…… 134

7.5 Drone inspecting pipeline ………………………………………………… 136

7.6 Gateway with IoT cloud …………………………………………………….. 137

# LIST OF TABLES

1.1 Year wise Pipeline failure incidents………………………………………. 5

1.2 Technologies used by organization to monitor infrastructure of oil field………… 15

2.1 Comparison of Steel pipe and Thermoplastic pipe……………………………… 24

2.2 Comparison various Pipeline leaks detection and localization methods……. 27

2.3 Comparison of IoT wireless communication protocols……………………... 35

2.4 Comparative Study of IoT-Based Pipeline Monitoring Approaches ……….. 40

4.1 LoRa network parameters………………………….................................. 73

4.2 Received signal strength of Lora with distance……................................... 73

4.3 Time on Air with various SF………………………….............................. 74

4.4 Signal to noise ratio with distance……………………............................... 75

4.5 Packet error rate with various SF……………………................................ 77

4.6 Bit rate with various SF at 4/5 code rate…………………….................... 78

4.7 Receiver sensitivity at various spreading factors…………………………........ 80

4.8 LoRa trades with Link budget with Antenna power at SF-7………............ 81

4.2 Parameter of Zigbee configuration ………………...................................... 83

4.3 Results achieved ……………………………………………………...... 87

6.1 Flow rate varying with diameter of the pipe…………………………....... 108

6.2 Natural frequency of pipes with various moment of inertia………………… 115

6.3 Summary of Case-II data analysis…………………………………………...... 116

6.4 Summary of Case-III Data analysis…………………………………………...... 123

6.5 Power consumption analysis…………………………………….............. 129

# LIST OF ABBREVATIONS

| | |
|---|---|
| **PHMSA** | Pipeline and Hazardous Materials Safety Administration |
| **LoRa** | Long-range |
| **MAC** | Medium access control |
| **SCADA** | Supervisory Control and Data Acquisition |
| **PLCs** | Programmable logic controllers |
| **RTUs** | Remote terminal units |
| **HMI** | Human-Machine Interface |
| **WSN** | Wireless sensor network |
| **WPAN** | Wireless personal area network |
| **LPWAN** | Low power wide area network |
| **PAN** | Personal area network |
| **ZDO** | ZigBee device objects |
| **PSDU** | PHY service Data Unit |
| **CR** | Code Rate |
| **BW** | Bandwidth |
| **SF** | Spreading Factor |
| **LoRaWAN** | LoRA wide area network |
| **SNR** | Signal-to-Noise ratio |
| **FSPL** | Free space path loss |
| **LCD** | Liquid crystal display |
| **PDR** | Packet Delivery Ratio |
| **APS** | Application Support |
| **PAN ID** | Personal Area Network Identifier |
| **IP** | Internet Protocol |
| **SOC** | Safety Operation controller |
| **HDPE** | High density polyethylene |
| **PVDF** | Polyvinylidene fluoride |

| | |
|---|---|
| **ISM** | Industrial, scientific and medical |
| **IoT** | Internet of Things |
| **ZDO** | ZigBee device objects |
| **FEC** | Forwarding error correction |
| **PER** | Packet Error Rate |
| **UAV** | Unmanned Aerial vehicles |
| **GPR** | Ground penetration radar |
| **Wi-Fi** | Wireless Fidelity |
| **NB-IoT** | Narrowband IoT |
| **CAD** | Computer-Aided Design |
| **GUI** | Graphical user Interface |
| **AFSS** | Attitude Flight Stabilization System |
| **ESC** | Electronic speed control |
| **BLDC** | Brushless Direct Current |

# CHAPTER-1

# INTRODUCTION

The background of the oil industry and its functioning is presented in this chapter. The significance and challenges in oil pipeline management are addressed with statistics data. The existing methodologies in pipeline monitoring, communication protocols, UAV, and renewable energy are discussed. Finally, research objectives are framed toward research and discussed thesis organization.

## 1.1 Background

The gas and oil industry is one of the world's most valuable industries in terms of revenue, earning an estimated $3.3 trillion yearly. The top oil producers are Saudi Arabia, Canada, the United States, China, and Russia. India is the third-largest energy consumer in the world. Bharat Petroleum, Oil and Natural Gas Corporation Limited (ONGC), Hindustan Petroleum Corporation, Indian Oil Corporation (IOC), and Reliance Petroleum Limited are some of the major oil producers in India. Upstream, midstream, and downstream are the three tiers of the oil industry. The world's oil production statistics are represented in the figure1.1 [2].

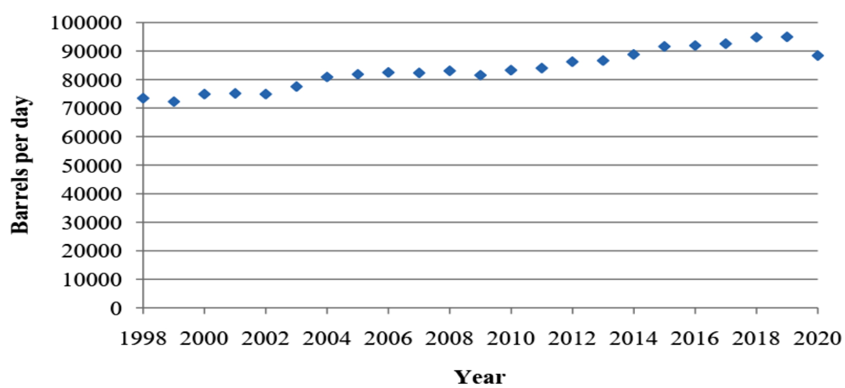



Figure 1.1Oil production statistics in World [2]

The upstream is involved in searching for raw materials as well as exploration from underground and underwater sources to bring crude oil to the surface [1]. The middle stream subdivision refers to the transportation of crude oil to processing plants or refineries in downstream sectors via pipelines, trains, trucks, and other means. In the purification and refining of crude oil, the downstream industry plays a crucial role. At this point, items created from raw petroleum and combustible gas are marketed and disseminated. Through downstream operations, buyers receive items such as petroleum, kerosene, diesel oil, and a range of petrochemicals. Figure 1.2 depicts the three subdivisions of the oil industry and their responsibilities.

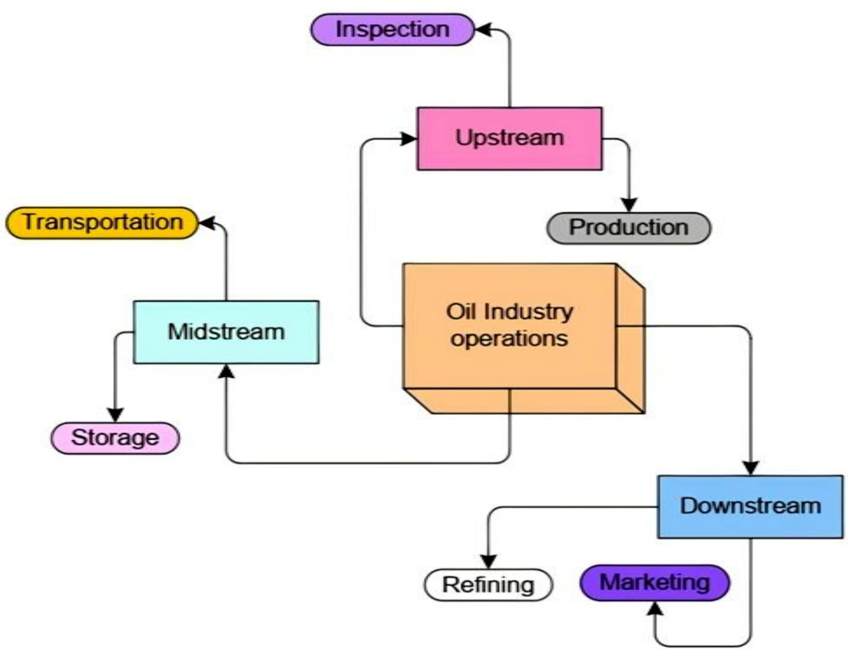



Figure 1.2 Oil industrial operation Sectors [1]

Midstream plays a key role in transporting oil in various modes. Oil pipeline transportation has several advantages, including reliability, stability, cost savings, and improved performance. Some of the biggest difficulties that the petroleum industry is dealing with in the midstream sector, particularly in terms of sustaining a long-distance pipeline network that spans more than 3 million kilometers worldwide. India is reported to have a total crude oil pipeline length of 10,419 km by the year 2020, with an additional

18,169 km of pipes installed for the transportation of oil products and oil transportation in various modes as shown in figure1.3 [2]. Pipelines are widely recognized as an important means of transporting petroleum products that contribute to a nation's economy [3]. Pipelines are the most cost-effective and secure way to transport crude oil, and they meet the increasing need for quality and consistency [4][5][6]. The pipeline is widely used for oil transportation around the world to overcome and minimize disasters caused by transportation.

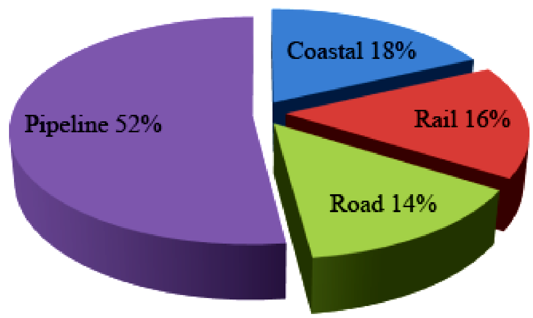



Figure 1.3 Various modes of Oil transportation [2]

With a total length of 5301 km, IOCL is involved in 50.88 percent of the country's crude oil pipelines. However, the state-owned Oil and ONGC has the largest volume share in crude oil transportation [2]. Figure.1.4 shows the oil pipeline capacity of various companies.

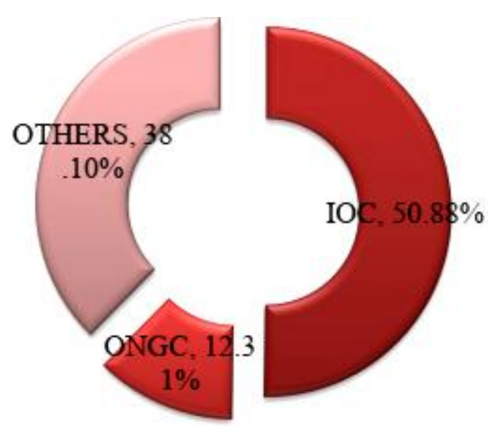



Figure 1.4 Pipeline network of oil companies [2]

The large implementation pipeline, on the other hand, has raised the probability of pipeline failures [7]. Some authors examined the issues and advocated for the seamless flow of oil through pipelines [8]. Pipelines that are not carefully maintained may fail, resulting in serious, long-term, and permanent effects for both natural and human surroundings as shown in figure 1.5.

Figure 1.5 Oil spills due to Pipeline failure [6]

According to the Pipeline and Hazardous Materials Safety Administration (PHMSA), there have been 3978 hazardous line liquid accidents between 2010 and 2019. Figure 1.6 addresses the reasons for these incidents in table 1.1 [9].Corrosion is the most frequent cause of oil pipeline damage [10].

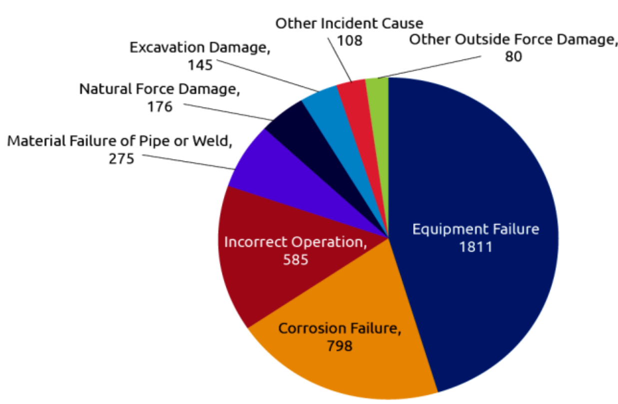



Figure 1.6 Oil pipeline causes [9]

Table 1.1. Year wise Pipeline failure incidents [9]

| **Year** | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Incidents** | 340 | 344 | 366 | 401 | 455 | 460 | 420 | 415 | 405 | 362 |

## 1.2 Oil Pipeline Monitoring Technologies

Pipeline transportation of crude oil is becoming increasingly vital in the global economy, yet oil pipeline leakage becomes an issue for the industry. Pipeline leakage monitoring and location are critical from both a social and economic perspective as well as an environmental and energy perspective. Many methods that have emerged as pipeline leak detecting technology has progressed in [11]-[13]. In this section, we'll go over the various ways of detecting leaks in oil pipelines as shown in figure 1.7.

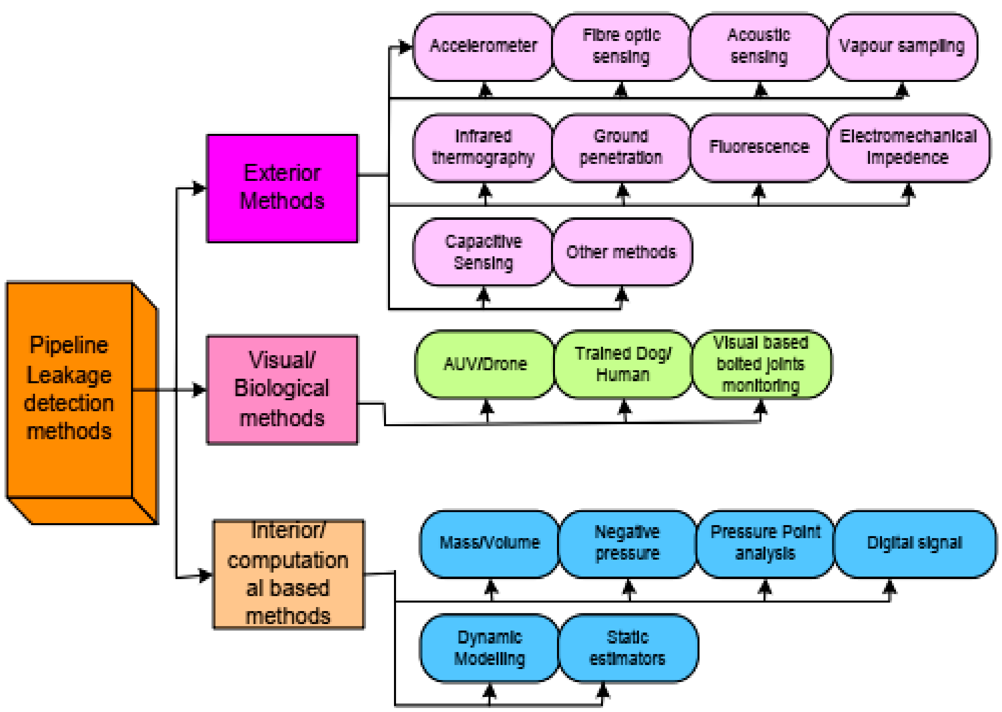



Figure 1.7Pipeline leakage detection methods [12]

Different strategies were used by the researchers in prior investigations to detect pipeline leaking. The methods are shown in the figure.1.7 and, on a technical level, the approaches are divided into three groups [11]-[13] namely interior, biological, and exterior methods. Exterior approaches are commonly used to detect leaking of the pipelines' outside layer and surrounding environment using different sensors. The vibration that happens during the leaking in the pipeline is measured using an accelerometer sensor [14]. For detecting hydrocarbon spills, fiber optic sensors are also put in a scattered style along pipelines. The high frequency 1 MHz vibrations that occur during pipeline leaking are detected using an acoustic sensor [15]. Vapour sensing detects the level of hydrocarbon vapor in pipeline's surroundings. The employment of an infrared thermography (IRT) camera to measure Differences in the pipeline system's temperature is beneficial. Water concentrations, landfill waste, and buried pipelines are all identified and inspected using Ground-Penetrating Radar (GPR) [16]. Fluorescence was a light-based technology for detecting the incidence of hydrocarbon leakage. Electromechanical transducers are constructed of piezoelectric patches of varying sizes with a dynamic impedance of less than, and their dynamic impedance is monitored to detect leaks. This approach detects the presence of hydrocarbon spillage by measuring the improvement in the dielectric of the substance in the sensor's environment [17]. Biological spill detection techniques are similar to the conventional method for locating spills in pipeline environments, which involves the use of expert workers, helicopters, and drones. Generally, trained employees can detect leaks by smelling the odor and observing the situation visually. Offshore oil transport companies' efficiency has improved due to Remotely Operated Vehicles (ROV).ROVs have proven to be dependable for doing subsea pipeline inspections and functioning in deep water where humans and other objects are not accessible [18]. Internal fluid analysis equipment is used by interior or analytical instruments to study fluid flow metrics inside pipelines, and flow rate, pressure, volume, and temperature are also measured inside pipelines during oil transit. Negative pressure waves, pressure point analysis, dynamic modeling, are among the approaches used to estimate the risk of leakage using information collected from the inside.

In oil pipelines, remote access increases leak detection and reliability. Remote monitoring aids appropriate authorities in obtaining important information about pipeline health. This allows authorities to react quickly to avoid harm and loss of essential oil being transported from a remote region. Helicopters, smart pigging, and sensor networks are used to implement remote monitoring [19]-[21]. In recent years, a wirelessly delivered remote information estimation unit has been used to assess and monitor process activities and make an informed decision in the event of a terrible disaster [22]-[24]. Automatic monitoring systems that use the PID controller can keep dynamic transport operations running smoothly and efficiently [25]. Modern control systems must emphasize protection since manual systems only have a 68 % adequate return. As a result, the need for intelligent regulation and monitoring has increased in recent conditions, reducing the device's optimal efficiency [1]. Supervisory Control and Data Acquisition (SCADA) is a system that combines hardware and software to do the following tasks: remotely or locally supervise the mechanism of an industrial process, receive and Analyze actual information and store a track of your activity [26][27]. The SCADA software can analyze, communicate, and visualize data to aid operators in making vital decisions [28-29]. Authorities can receive information from SCADA systems and send it to specialized systems that are based on software.

### 1.3 Communication Protocols

Communication protocols are of digital message formats and rules. It is essential to consider an effective protocol that defines specific rules, norms, or recommendations for any data transmission within a network. Secure communication between multiple network nodes for data exchange can be formed with the help of such a protocol. Here, WPAN-based Zigbee and LPWAN-based LoRa communication is discussed. These communication protocols use very little power to transmit data reliably and effectively.

One communication protocol creates a wireless personal area network (WPAN) among the nodes, while another creates a low power wide area networks (LPWAN).

**a) Zigbee Protocol**

Zigbee is an IEEE 802.15.4-based wireless communication system that allows you to establish a low-energy personal area network (PAN) [37]. Because it uses less energy for data transfer, Zigbee extends the battery life of end devices. Figure 1.8 depicts the Zigbee architecture, The physical layer, the Medium Access Control (MAC) , the network layer, and the application layer are the four layers [38][39].

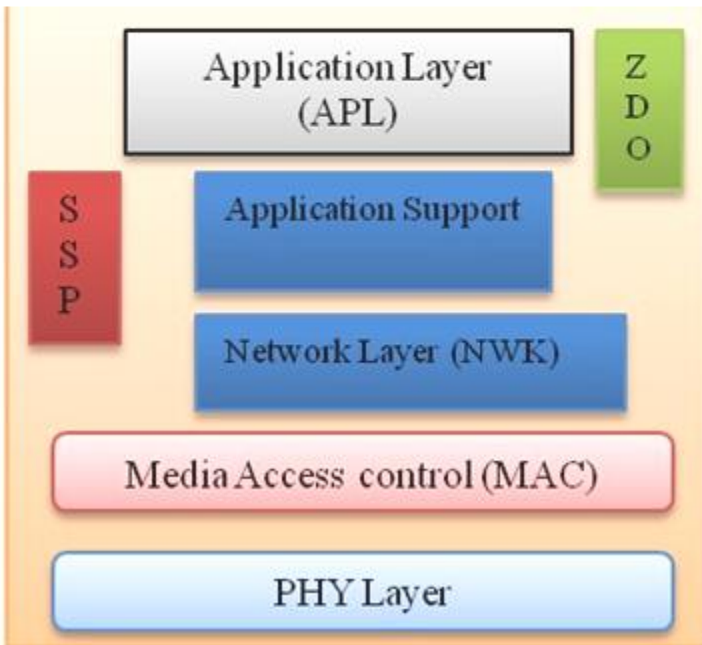



Figure 1.8 Zigbee Architecture [38]

The application layer includes the Zigbee device objects are system management and information gathering application. The Zigbee wireless sensor-to-device and device-to-device communication standards are rapidly growing in the field of the Internet of Things (IoT). Zigbee is utilized in a variety of applications, including industrial Sensors and controllers, intelligent power management, healthcare, environment monitoring, building automation, and sound detection are some the technologies that are being developed[40][41]. The use of WSN and Zigbee in space communication and monitoring systems is examined [42]. The Zigbee network is made up of three components: a Zigbee Coordinator, Zigbee end devices, and Zigbee routers.

End devices handle the majority of a Zigbee network's power-saving functions. Because these nodes aren't used for traffic routing, they can sleep for the majority of the time, extending the battery life of these devices.

This coordinator node is in charge of setting up the network, choosing a suitable channel, and allowing other devices to join to it. In a Zigbee network, it can also be in charge of traffic routing.

A router can transmit and receive messages and link to child nodes in network, which could be another router or an end device.

**b) LoRa Communication Protocol**

LoRa is a spread-spectrum communication protocol that uses unlicensed ISM groups, such as 868 MHz in Europe, 433 MHz in Asia, and 915 MHz in North America [42]. The PHY layer is represented by many characteristics including Spreading Factor (SF), Bandwidth (BW), and Code Rate (CR), and Power in a few works that illustrate highlights of LoRa technology. At the same time, messages delivered utilizing specified spreading elements can be received by LoRa access points. LoraWAN provides bi-directional availability across long distances at 0.3 to 50 kbps data rates are available. LoRa endpoints can be used in a variety of ways. In general, the LoraWAN provides three types of endpoints [12].

A two-way connection is provided using LoraWAN Class A terminal devices. To this objective, each endpoint transmission is provided with two slots for brief downlinks. It is programmed by same endpoint is determined by the endpoint's requirements, and tiny changes are frequently calculated in a frequent basis. It is the most energy-efficient option for endpoints that only require downlinks from the server following a transmission from the end device to the uplink. Before the next upload time is specified, download the server messages.

Class B LoRa systems provide Class A capability and frequently open extra windows at predetermined intervals. To complete the necessary network synchronization, the endpoint receives from the gateway. This enables the server to understand what is happening when the device is receiving.

On LoRa Class C devices, reception windows are usually constantly open. After the endpoint has been transmitted, they are locked. This endpoint type is appropriate for receiving rather than transmitting large amounts of data.

Figure 1.9 shows the LoRa network's basic architecture, which is made up of end nodes, gateway, and servers.

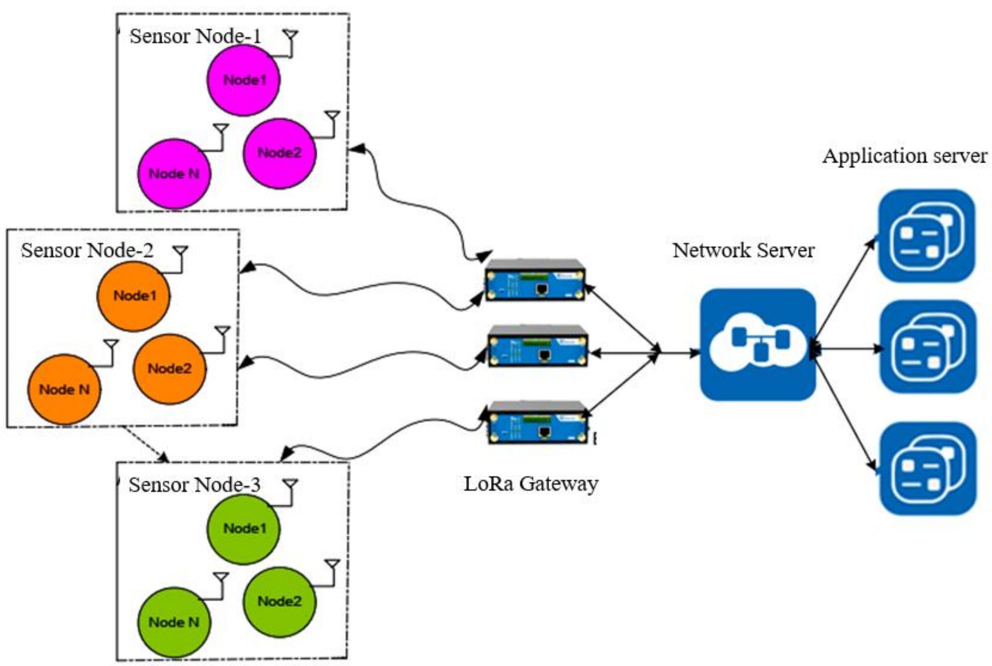



Figure 1.9 LoRa Architecture [12]

The LoRa protocol's end nodes are used to send small amounts of data across great distances at low frequencies. Farm automation, smart buildings, drones, and industrial automation are some of the uses for LoRa end nodes. End nodes have the following functions: End nodes were integrated with LoRa chips, and sensors in the end nodes were used to detect important characteristics such as temperature, noise, pressure, and humidity. Remote devices and processes are controlled via controllers. The LoRa gateway receives the packets and forwards them to a network server. The end node receives packages via a radio link. The gateways between a network server and end nodes in the LoRa WAN are intermediate. End nodes provide data packets to the network server through gateways, and vice versa.

Entire network managed by network server. Packages and free packets are subjected to redundancy and security tests upon reception. The recognition message is then returned through the gateway. Both uplink and downlink connectivity is available to network servers. In this case, up and down means wireless device sensors and vice versa Application Server: All data is sent from end PCs to the end server application server. These servers provide capabilities for processing data from network servers and displaying it as a chart on a webpage or in an app. The LoRa modulation is controlled by three important parameters: spreading factor (SF), Bandwidth (BW) and coding rate (CR).The chirps created by every sign are measured in SF, which ranges from 7 to 12. The higher the SF value, the better the receiver's signal noise reduction will be. The longer a packet requires delivering, the longer it takes to transfer.

Carrier frequency refers to the frequency of a carrier wave that has been changed to transport signals. The SX 1278 transceiver uses a 433 MHz carrier frequency.BW represents the frequency in the spectrum band, which can be one of three bands: 125 kHz, 250 kHz, or 500 kHz. A large bandwidth denotes faster transmission, whereas a narrow bandwidth denotes long-distance communication. In LoRa modulation, BW is the most essential parameter. The 2SF chirps that make up the entire frequency range are represented by the LoRa symbol. It begins with a series of escalating chirps, and when the highest frequency band is reached, the frequency is covered, and the frequency is increased from the lowest. The chirp spread spectrum (CSS) modulation technique is utilized in LoRa communication. Chirp is a signal whose frequency alternates between increasing and decreasing over time.

**Spreading Factor**

The number of chips used to display a symbol is determined by the Spreading Factor (SF) value. The equation 1 and 2 are listed below shows the relationship between the Spreading Factor (SF) and bandwidth (BW).

$$SF=\frac{Chiprate}{Symbolrate} \quad \text{-- 1.1}$$

$$T_S=\frac{2^{SF}}{BW} \quad \text{-- 1.2}$$

Where $T_S$ is the symbol period.

**Code rate**

The coding rate (CR) transports genuine data and guarantees that interference is kept to a minimum during transmission. It has a range of CR1 to CR4 and is utilized for forwarding Error Correction (FEC).CR represented as

$$CR=\frac{4}{4+n} \quad \text{-- 1.3}$$

Where n ranging from CR1 to CR 4

**Time on Air**

TOA is the length of time that passes before a receiver hears a signal. The TOA of a packet is calculated using a mix of BW, CR, and SF.

LoRa packet structure is shown in figure 1.10. The length of the preamble is given in the equation.

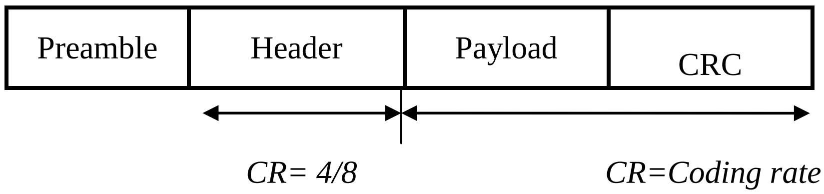



Figure 1.10 LoRa Packet Structure

$$T_{Preamble} = (n_{Preamble} + 4.25)T_{Symbol} \quad \text{-- 1.4}$$

**Bit Rate**

The speed at which bits are transmitted from one point to another is referred to as bit rate or data rate. The LoRa data rate is calculated as follows:

$$R_b = \frac{SF * BW}{2^{SF} * CR} \quad \text{-- 1.5}$$

**Link Budget**

A link budget is the sum of all gains and losses from the transmitter to the receiver through the medium in a telecommunication system. It is a method of calculating the link's performance.

$$Link\ (dBm) = (Antennatransmitted\ (dB)) - (Nodesensitvi(dB)) \quad \text{-- 1.6}$$

**Packet Error Rate (PER)**

Calculate the PER by dividing the total number of packets received by the total number of error packets after forwarding error correction (FEC). A packet is a data unit that is susceptible to FEC in a radio broadcast.

**Receiver sensitivity**

The receiver's sensitivity is defined as its capacity to amplify weak signals received by th e receiver. The spreading factor, noise figure, and bandwidth are regarded inputs in LoRa , while the sensitivity is provided as an output. Sensitivity ($S$) is calculated in equation-7

$$S = -174 + 10log10\ BW + NF + SNR \quad \text{-- 1.7}$$

## 1.4 Unmanned Aerial Vehicles

Monitoring oil pipeline networks necessitates a regular examination of the pipes' physical state and functionality to reduce the danger of leakage, and theft, as well as documentation of accidents with their environmental consequences. Detailed mapping for monitoring entails establishing a baseline state and identifying any changes that occur throughout the pipeline's life. n the past, volume and balance data were employed to monitor pipeline networks. Currently, the majority of monitoring is still done using traditional means, primarily by manual patrol and observation utilizing helicopters [46]. UAVs can fly autonomously or remotely controlled from another location [47]. Drones were first used by the military, but these UAVs with IoT add-ons are now widely used in civil applications such as infrastructure inspection, community security, traffic control, cattle ranching, and precision agriculture surveillance, providing us with several advantages. UAVs will be a cost-effective solution in the building industry [48][49]. These IoT-enabled UAVs can fly above objects with pinpoint accuracy and take the highest-quality photos with a high-resolution camera, which can then be processed using machine and IoT algorithms to track the development of any building site, whether connected or not. The number of drones can be raised for non-connected sites, and they can work in a master-slave configuration [50] to update the findings, whilst the update for related locations can be acquired by utilizing the right flight schedule.

Various UAVs showed in figure.1.11. UAVs are at the forefront of digital usage in the oil sector, overcoming the limitations of various inspection methods, monitoring, and surveillance tasks. Asset integrity management in the oil and gas industry frequently involves inspections at heights, on operational systems, or in restricted regions. Rope, scaffolding in certain situations and a full-size helicopter are employed to access these difficult-to-reach regions. By employing UAS to conduct pipeline patrols, problems associated with traditional pipeline monitoring may solve and various UAV systems are elaborated for a different purposes[55]. Researchers elaborated on different UAV systems for various purposes [60]. Table.1.2 shows the organization which used technology for pipeline inspections. Horizontal takeoff and landing (HTOL) and vertical takeoff and landing (VTOL) are the two basic landing techniques used by UAS (VTOL). Although HTOL UAS have a fast cruise speed, they are difficult to control for landing on a specified location and cannot move vertically or hover. This category includes the majority of traditional aircraft. VTOL UAS, on the other hand, are capable of flying, landing, and hovering vertically but are not ideal for greater cruising speeds. UAVs with fixed wings are comparable in shape to commercial passenger and freight planes, and they fall within the HTOL category [60].

Table1.2 Technologies used by organization to monitor infrastructure of oil field

| **Organization** | **Task** | **Technology** |
|---|---|---|
| British Petroleum and AeroVironment [56] | Inspection of infrastructure of oil filed | UAV with LiDAR or IR |
| ConocoPhillips and Boeing [57] | Arctic marine creatures and ice areas are being studied. | UAV with IR imagers and video |
| British Petroleum and University of Alaska Fairbank [58] | Pipeline inspection for leak detection | UAV with IR cameras |
| Aeronautics[59] | Patrolling offshore field | UAV with IR camera |

Figure 1.11  UAS systems. a) Quadrotor (b) Fixed-wing [48]

### 1.5 Renewable Energy

Renewable energy is a word that refers to energy sources that can be regenerated spontaneously, such as energy derived from the environment. Solar, geothermal, wind, and hydropower are among them. The energy obtained by harnessing the Sun's heat and light is referred as solar energy. There are many methods to make use of this bountiful resource to technological advancements. Because it does not emit greenhouse gases, it is regarded as a green technology. The approach is thermal conversion, in which sunlight's The first method involves heating a medium that passes through a generator turbine, while the second method involves photovoltaic conversion, which involves converting light energy to electrical energy without the use of moving parts or ionization [51]. On bright sunny days, harvesting of solar energy based on photovoltaic technology delivers a maximum power density of about 14mW/cm2 [52][53]. When used for energy harvesting wireless sensor networks, photovoltaic harvesters have numerous advantages. Solar energy has been one of the most practical, dependable, and preferred energy-harvesting methods accessible in wireless sensor networks since its inception. Photovoltaic harvesters supply continuous current and direct current to sensor nodes. As a result, they don't need any further circuit rectification, such as changing alternative current (AC) to direct current (DC).

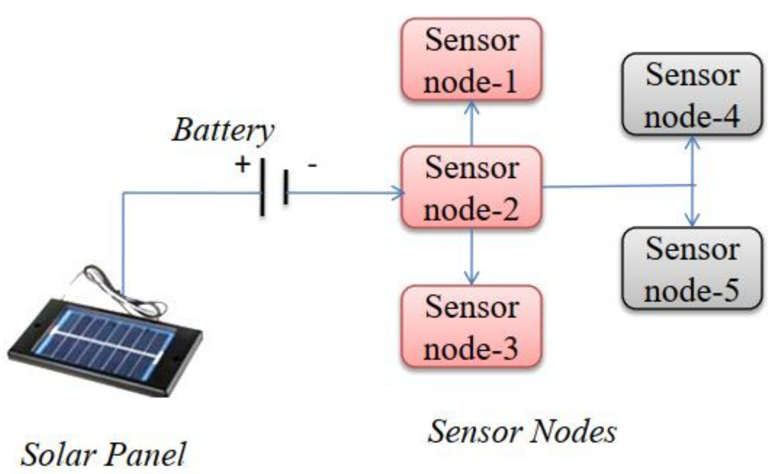



Figure 1.12 Solar-powered sensor nodes [54]

The solar energy collecting method is non-toxic and non-emitting to the pipeline field and voltage and current levels satisfy the power needs of WSN nodes. This approach makes solar energy an appropriate and most suitable energy harvesting technique for pipeline monitoring [54]. The process for creating an energy harvester for wireless sensor nodes is shown in figure 1.12.

## 1.6 Research Objectives

- **i.** Deploying end sensor nodes on the pipeline
- **ii.** To monitor pipeline parameters
- **iii.** To establish a network between sensor nodes and LoRa gateway
- **iv.** To design a drone for on demand visual data collection
- **v.** Data analysis and forecasting with Internet of Things

## 1.7 Thesis Organization

**Chapter-1** introduces the oil industry, Oil Pipeline monitoring technologies, and numerous communication protocols such as Zigbee and LoRa to the oil sector in pipeline management. Moreover, research objectives are framed.

**Chapter-2** gives a comprehensive analysis of the literature on the oil industry, pipe and their materials and wireless sensor networks (WSNs), and the Internet of Things (IoT). Finally, reviewed existing approaches of oil pipeline monitoring and research gaps are identified.

**Chapter-3** presents the system architecture and its sub-modules for oil pipeline monitoring. This study highlights the significance and process of each module block diagram, simulations on proteus software, PCB design, and circuit. Finally developed customized hardware nodes. Methodologies of the hardware realization of all modules with their customized hardware prototype are discussed.

**Chapter-4** gives an outline of network performance evaluation of various parameters of LoRa and Zigbee communication protocols and set the parameters for real-time implementation. Moreover, power analysis and battery life of sensor nodes and sensors have been analyzed.

**Chapter-5** presents the design of a quad copter drone with AutoCAD and simulations are generated. Moreover, the assembling of drones for oil pipeline inspection with various IoT components is discussed.

**Chapter-6** presents data analysis acquired from the field of sensor nodes of the pipeline are analyzed in various cases and designed an algorithm for pipeline leak finding. Finally, power consumption analysis is discussed.

**Chapter-7** gives the outcome of the objectives including publications. Moreover, the chapter presents the novelty of work along with future scope is discussed

### 1.8 Chapter Summary

This chapter outlines the oil industry and the importance of the midstream sector, particularly the transportation of oil through pipelines. Various pipeline maintenance issues that the oil sector is experiencing are discussed. Other researchers' oil pipeline monitoring methodologies are presented, and research objectives are framed. Communication protocols such as LoRa and Zigbee, which play a key part in this study, are also mentioned. The use of UAVs for on-demand visual inspections of pipelines when problems arise, as well as the use of renewable energy to power sensor nodes in remote monitoring, is explored.

# CHAPTER-2

# REVIEW OF LITERATURE

This chapter presents a foundational understanding of the oil industry and Pipes and their materials, oil pipeline management, and their issues. Furthermore, Wireless Sensor Networks (WSN), Internet of Things (IoT) technologies is addressed, and various communication technologies are discussed. We also discussed several research studies relating to oil pipeline management, highlighted research gaps.

## 2.1 Oil Industry

Oil and gas are strategically important to a country's economic success. Crude oil is one of the world's most valuable commodities today. Its diverse variety of applications includes anything from energy production to use as a feedstock for transportation fuels and petrochemical products including polymers, solvents, and adhesives. Oil and gas energy's importance to human activities, as well as its enormous impact on the economies of both oil-producing and oil-importing countries, cannot be overstated. As a result, the oil industry is one of the world's most powerful businesses, and variations in benchmark oil prices have significant for most manufacturing sectors and consumers [61]. Pipelines are most cost-effective and secure way to transport oil and gas between upstream oil reserves to downstream consumers. If the pipeline fails by accident, it will cause widespread damage and instability in society [62]. Pipeline operators must be able to recognize to avoid disruption in regular operations. Pipeline risk has been a major subject among international pipeline operators as they try to figure out how to make pipeline transit safe and efficient [63-69]. Many studies of the danger of pipeline operating have been carried out from diverse perspectives. In India, for instance, the hazards of installing inter oil pipes are examined [63]. The hazards of a construction are investigated and applied to the development of a petroleum pipeline in India [64]. Pipeline risk assessment is being explored in the example of Savadkooh in Iran [65]. The risk of landslides during the building of a lengthy China's oil pipeline construction is analyzed [67]. In a range of operating circumstances, the efficiency and danger of a coastal oil pipeline transport network are analyzed [68]. To accommodate for the uncertainty, the pipeline hazard is modeled using a fuzzy approach [69]. Pipe substance, hardware problems, and corrosion, pipe substance, and hardware problems are the three most common causes of oil pipeline spills is the three most common causes of oil pipeline spills. Corrosion is an unsafe and unfathomably over-the-top issue. Because of it, structures and platforms can fold, oil pipelines break, and substance plants spill. Consumed electrical contacts can cause fires and different issues. For oil pipelines, corrosion is a huge factor in pipeline failure. Among those, external corrosion normally represented over 60%, predominantly galvanic erosion, while internal corrosion is primarily of microbiological consumption. For oil pipelines, corrosion is a huge factor in pipeline failure. Among those, external corrosion normally represented over 60%, predominantly galvanic erosion, while internal corrosion is primarily of microbiological consumption [10]. Figure 2.1 shows Barrels of liquid spilled from oil pipelines from the year 1985 to 2015 [70].

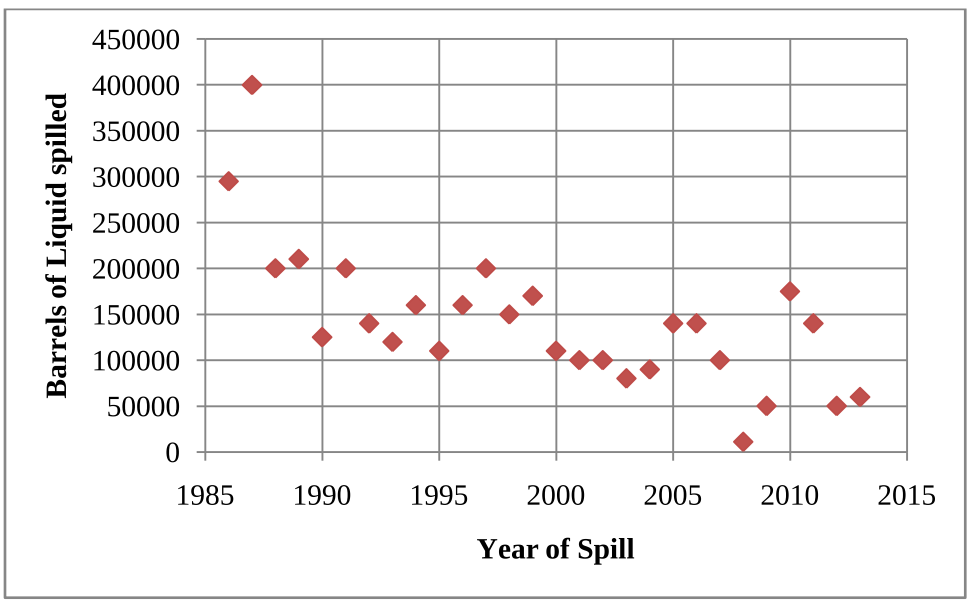



Figure 2.1 Barrels of liquid spilled [70]

People and organizations associated with the pipeline organization may cause third-party damage by diving in the region of covered pipelines without recognizing the pipeline is there or without considering the pipeline's location. This type damage is common in and around cities and towns, and can be caused by large-scale removal projects, development activity, and farming activities.

### 2.2 Pipes and materials

Fossil fuels, such as oil and natural gas, comprise the majority of energy resources. Consequently, it is imperative to generate and transport them at a reasonable cost. Pipelines play a pivotal role in transporting oil over long distances, often to markets for consumption. Across 120 countries in the world, a total of less than 3,500,000 km of pipeline is in use for oil and gas transportation. Transporting oil through pipelines accounts for 52% of India's oil traffic [2].

#### a) Steel pipes

Steel pipes are lengthy, hollow tubes that have a variety of applications. They can be either welded or seamless, i.e., raw steel is initially cast into a more practical form for both methods. A seamless tube is formed by stretching or forging the steel into a pipe by forcing edges together and joining them. Figure.2.2 shows the basic steel pipe.

Figure 2.2 Steel pipes [184]

Today, steel pipes are the primary means of transporting oil and gas over long distances. Corrosion has been identified as a primary reason for oil infrastructure failures, as shown in figure 2.3. Around 30-40% of oil pipeline failures are due to corrosion [9]. Corrosion is caused by chemicals such as naphthenic acid (NA) reacting with iron particles or forming a surface film; in the hydrocarbon industry, this happens with sulphur particles (S). However, the rate of corrosion is affected by the crude oil's quality, its acidic contents, and the transport environment [184]. It's important to keep this pipeline infrastructure from being damaged by the surroundings that could result in financial loss [186][185].In addition, pipeline interior corrosion appears to be a significant concern at the earliest stages of production [187]. A total of 9000 failures were observed due to interior corrosion from 1990 to 2012 [188]. Sources of corrosion are hydrogen sulfide (H2S), chlorine, carbon dioxide (CO2), and oxygen. Corrosion comes in a variety of forms and reasons. The issue of sweet corrosion (CO2) has been recognized for many years in oil and gas production and transportation infrastructure. CO2 is one of the most common corroding substances in the oil and gas industry [189][190]. Sour corrosion is the deterioration of metal caused by contact with hydrogen sulphide ($H_2S$) and moisture. Though $H_2S$ is not corrosive in and of itself, it becomes a highly corrosive substance when combined with water [191].

Figure 2.3Steel Pipes affected by corrosion [187]

Galvanic corrosion is caused by the contact of two metallic substances of different nobility with an electrochemical environment [192]. Metals react rapidly with oxygen, a powerful oxidant. In cathodic processes, oxygen promotes anodic degradation of a metal by acting as a depolarizer and electron acceptor [193]. As a result of erosion-corrosion, corrosion accelerates by repeatedly corroding the protective coating. An increased air-fluid motion is always associated with a higher corrosion rate [194][195]. Biological wastes such as CO2, H2S, and organic acids cause pipes to degrade by increasing the toxicity of fluids passing through [196].

**b) Thermoplastic Pipes**

Nonmetallic pipe materials are made up of polymers and composites and have been utilized as inner fillers for a long time. The use of thermoplastic liners for remediation of internally corroded pipes is a viable alternative for extending pipeline lifespan and lowering operational costs. Europe and North America were the first to employ this relining procedure. They feature several distinct characteristics, including lightweight, corrosion resistance, chemical inertness, and good heat and combustion resistance [197]. In comparison to other preventive actions, such as coatings and chemical treatment, thermoplastic liners were also created to manage subsea failures in oil production [198]. The most popular thermoplastic materials used in the pipeline sector are high-density polyethylene (HDPE), polyamide (PA11, PA12), and polyvinylidene fluoride (PVDF). These are the raw resources that go into making the composite thermoplastic pipe [199]. It builds a large amount of oil and gas pipelines [200]. Semi-crystalline, high strength and low density are all desirable qualities [200-202]. They have lower thermal conductivity and a smoother pipe surface [203]. A thermoplastic pipe as shown in figure.2.4 has various advantages over a traditional steel pipe, including improved corrosion and fatigue resistance, increased stiffness to weight ratio, and cheaper maintenance costs.

Figure 2.4 Thermoplastic pipes [197]

In spite of their less expensive base materials, pipeline applications have lower overall costs than steel ones, especially when considering the need to replace aging steel pipes [204]. The following are some of the benefits of polyethylene pipes: the pipes have a minimum service life of 40 years and a maximum service life of around 100 years; the weight of HDPE pipes is more than 5 times less than the weight of steel pipes with similar dimensions; no additional protective measures are required when laying on the ground because the material is highly resistant to corrosion and chemical attack.Table.2.1 gives the comparison of steel and thermoplastic pipe. The smooth internal layer of the pipes avoids sludge from depositing on the walls, thus the inside diameter of the pipes does not vary during service; when the fluid in the pipe freezes, the pipe will not burst since the substance can expand by 5%–7% [205]. HDPE PE100 pipe is simple to install, lightweight, flexible, corrosion-free and has a life span of up to 100 years. It has short-term burst pressure (STBPs) of up to 45.0 MPa and a maximum ambient fluid temperature of $65^{0}$C [206].

Table 2.1 Comparison of Steel pipe and Thermoplastic pipe

| **Characteristics** | **Steel pipe** | **Thermoplastic pipe** |
|---|---|---|
| Material | Primarily iron | Polyethylene |
| Corrosion | Steel pipes easily corrosive | Thermoplastic pipe never corrodes |
| Service life | Lesser than Thermoplastic pipe | Twice longer than that of metal ones (up to 100 years) |
| Transportation Speed | Transportation Speed is limited due to the rough inside face of steel pipes. | Smooth inside surface, which promotes transportation capacity. |
| Installation speed | 2km per day | Up to 10km per day |
| Weight | High | Less compared to steel pipe |
| Maintenance | High | Less compared to steel pipe |
| Cost | High | Less compared to steel pipe |
| Usage | Offshore and Onshore | Onshore |

## 2.3 Pipeline Leaks Detection and Localization Methods

Pipelines transport oil products like fossil fuels and gases important hydrocarbon fluids that benefit to the country’s economic growth. Pipelines that aren't properly maintained harm the environment. Pipeline leaks are difficult to completely avoid since the causes of failure are numerous. However, to decrease the societal effects of oil spills, Monitoring pipelines for spill detection is crucial, as early detection of spills allows for quick responses to stop oil discharge and proper pipeline repair. As a result, pipeline failures can result in fewer casualties, injuries, and other major socioeconomic and environmental effects. All throughout years, various spill detection approaches have been presented, each with its unique set of ideas and procedures. The fiber optic cable method shown in Figure 2.5depicts a fiber-optic link that extends of the pipeline and takes temperature measurements. When the materials to be assessed make contact with the link at the precise point a break happens, the temperature of the contact changes. It could be either a close-by cooling or warming system, depending on the type of material sent through pipe [71]. Mach-Zehnder-based optical fibre early warning system that includes the optical fiber and three Mach-Zehnder interferometers for altering the light speed [72]. The real constraint of fiber optic link strategy is the cable length and, the framework can never again work if the link is ended.

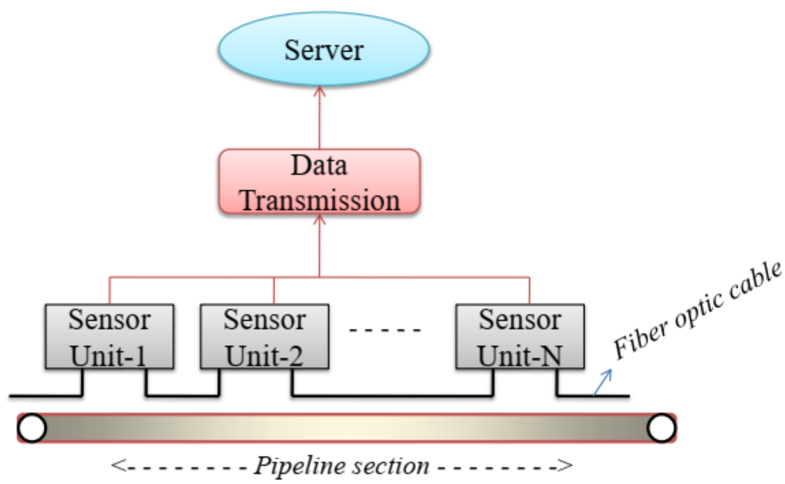



Figure 2.5 Fiber optic cable system[72]

Pipeline visual examination with CCTV causes for entries, cleared over sewer vents, pipeline breaks, and other assets can be refined without the hassles associated with pipeline revealing [73]. Ground penetration radar is becoming more popular as an ecological tool for identifying and distinguishing physical features such as buried pipes, groundwater focuses, and garbage waste in the ground [74]. GPR is a non-intrusive increased imaging tool that uses the propagation of electromagnetic wave and dissipating procedures to distinguish adjustments in the magneto electric features of the surface soil the pipeline [76]. Pipeline spillage recognition systems dependent on the infrared thermograph instrument are likewise appropriate for the identification of pipelines spillages. Pipeline spillage detection systems based on the infrared thermograph instrument are also suitable for detecting pipeline spillages that produce changes in temperature in the pipeline condition using thermal imaging with a wavelength range of up to 1400 nm [77]. The basic structure if IRT is shown in figure2.6.

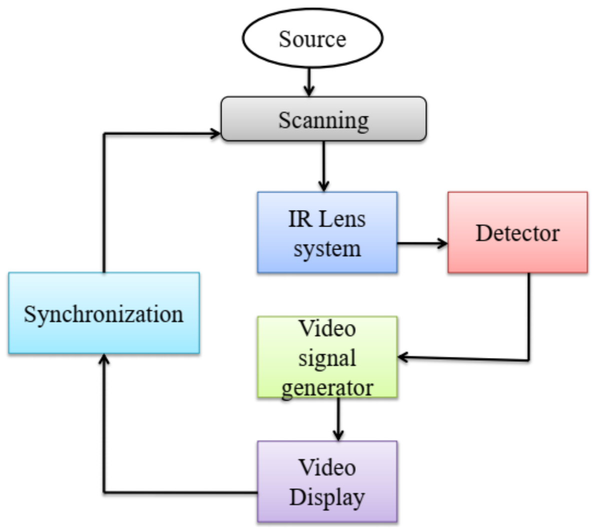



Figure 2.6 Fundamental elements of an IR Thermography camera [77]

Leak recognition in pipelines utilizing acoustic emissions innovation depends on the rule that getting away fluid makes a sound when spilling in the pipe [78]. At the point when a leak happens, the subsequent recurrence acoustic sign is recognized and broke down by framework processors. The received signal is more grounded close to the leak site henceforth stick pointing the area of the spilling focuses. In [79], the author displayed an examination that researches the natural properties of the vibroacoustic signals rather than relative amplitude values. Recently [80], provides a leak detection approach for water pipes under a variety of operating circumstances. Figure.2.4 shows the data acquisition setup for the water pipeline system. This system gives best results but the sensors need to be installed more throughout the pipeline. Accelerometers are another kind of vibroacoustic estimating gadget that is additionally helpful to screen low-frequency pipe-outside vibrations [81]. Some authors [82][83]remote accelerometers were used to distinguish spillage occurrences on the exterior of control valve that were associated with pipeline systems with some experimental analysis. The pressure point analysis technique is used to detect spills by comparing current pressure estimates to historical patterns of pressure estimates with flow rate along the pipeline during time [84] [85]. The pressure point analysis leak location strategy depends on the measurable thing pressure of the pipe before and after spillage happens [86][87]. This method is thought to be effective as probably the quickest method for recognizing the nearness of spillage in a pipeline dependent on the way that the presence of leak consistently brings about a quick drop of pressure at the leak point. Little spillages which can't be effectively distinguished by different techniques can be identified utilizing PPA. In any case, it is hard to decide the spill area utilizing this strategy [88]. Vapor sampling is a typical method for determining the amount of hydrocarbon vapor present in a pipeline. In the literature, various types of vapor random samples pipeline spill observing frameworks have been presented [90].

Negative pressure waves leak detection systems work on the principle that when a leak is discovered, the pressure of the pipe changes and the velocity of liquid flow changes throughout the pipeline. This approach is commonly used in pipeline monitoring because of its quick reaction time and whole localization capability. A negative pressure wave is supplied at the breakpoint due to the rapid weight pressure, which spreads at a particular speed towards the pipeline's input and output areas. In addition, the wave delivers spilled data that may be accessed by visual analysis and signal investigation to detect the spill zone, impacting the time required for the waves to arrive at pipeline closures [92]. Table 2.2 shows the pipeline leaks detection and localization methods

Table 2.2 Comparison various Pipeline leaks detection and localization methods

| Methods | Principle of operation | Leak localiza tion | Strengths | Limitations |
|---|---|---|---|---|
| Fiber Optics Sensing | Distinguish spills when the temperature of the | YES | It can function as both a sensor and a | Wired network |

| | | | | |
|---|---|---|---|---|
| [71] [72] | link's optical wave varies to the nearness of spillage. | | communication device. | |
| Acoustic Emission<br><br>[78] [79] [80] | Identify leaks by grabbing characteristic signals getting away from a punctured pipeline. | YES | Simple to install and reasonable for early location and compact. | Touchy to ecological noise and not reasonable for little spills. |
| Ground Penetration Radar<br><br>[74] [76] | It Transmits Electromagnetic Waves For Checking Objects By Moving An Antenna Along A Surface | YES | Underground Pipeline Leakages Are Recognized | This Gpr Signals Are Sensitive To Dirt Soil Conditions |
| Infrared thermography<br><br>[77] | Distinguish Leaks Utilizing Infrared Picture Strategies For Distinguishing Temperature Changes In The Pipeline Condition. | YES | It Gives Visual Pictures, Simple To Utilize | Not Possible With Obstacles |
| Vapour Sampling [90] | Distinguish follow convergences of explicit hydrocarbon mixes, use hydrocarbon vapour dispersed | NO | Suitable To Detect Small Leaks | Time Taking Method. |

| | | | | |
|---|---|---|---|---|
| | into the sensor cylinder. | | | |
| Pressure Point Analysis [85] [86] | Keep track of pressure variation at various focuses inside the pipeline system. | YES | Suitable for submerged conditions, cold atmospheres and satisfactorily working under assorted stream conditions. | Leak identification is tough where valves are opened and shut all the while. |
| Negative Pressure Wave [92] | Determine negative waves when pressure drops | YES | Quick reaction and reasonable for spill localization. | Methods that are more computationa l |

## 2.4 Wireless Sensor Networks

Wireless sensor networks are a collection of nodes with no infrastructure that monitor and collect data about their surroundings. Variables like temperature, pressure, and humidity are commonly included in this data. WSNs, in general, aren't just for data collecting; they can also integrate actuators to influence their surroundings [30]. Individual nodes collect and transfer data to one or more sinks regularly [31]. The sink processes and forwards the data to be used locally or uploaded to the cloud through a gateway as shown in Figure 2.7. For applications with a small number of nodes, a single sink WSN scenario is simpler, but it lacks scalability. A typical WSN includes several sinks and the ability to add more sinks to expand network capacity. Minimum delay, maximum throughput, number of hops, and protocol complexity are all criteria that influence the selection of several sinks [31].

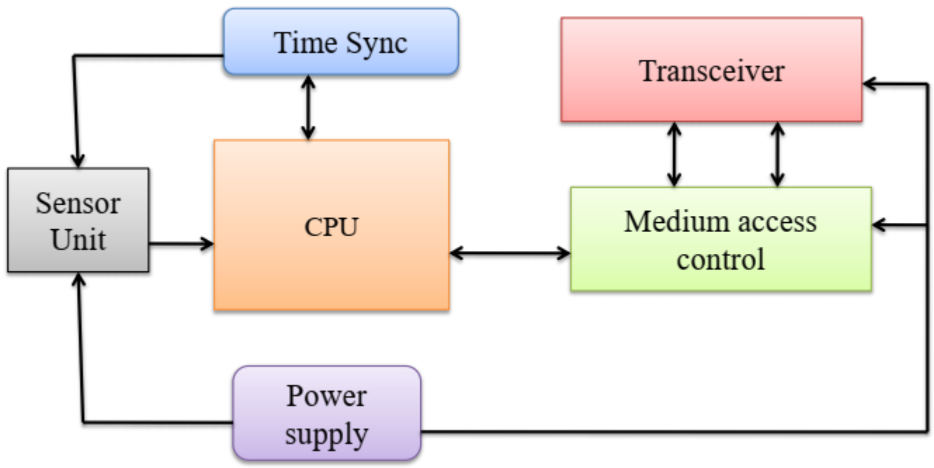



Figure 2.7 WSN architecture [31]

The WSN functions as a sensory nerve system that links the physical and digital worlds. It is a collection of small wireless electronic motes, also known as sensor motes. The capacity in serving security, surveillance, agricultural, and home automation, WSN is expected to be an economically viable model and a promising technology [32]. This method is widely used in the upstream oil sector to recover oil from the ground and midstream also [33][34]. Sensor network is employed in the purification process and in the preservation of oil in reservoirs in the downstream industry [35][36]. WSN is commonly used to develop automatic systems for monitoring the oil industry. In terms of real-time tracking, insights, and judgment, the WSN, on the other hand, has limits. For scientific community, Internet of Things is a rapidly increasing area of growth. By obliterating wired communication, single-function, and high-power consumption devices, the IoT evolutionary process has made room for wireless, multipurpose, and low-power gadgets. The Ethernet wire is then linked to the network gateway via DSL or cable. Wired networks are well-established technology that is simple to connect to provided you already have a phone, power, and coaxial cable lines. A WSN may undertake data acquisition of large regions by using of a sufficient number of such sensor nodes. Continuous technical advancements have made it possible to produce sensor nodes of this type at low cost and processing capabilities. As a result, while WSNs were designed primarily for military uses, they today serve a diverse variety of applications [95][96]. Its goal is to track and detect ecological occurrences for safety and environmental monitoring [97][98]. WSN is now being used in either mature or in the early phases of development. WSN applications are categorized in this article into six primary groups based on their intended usage [99], as shown in figure 2.8.

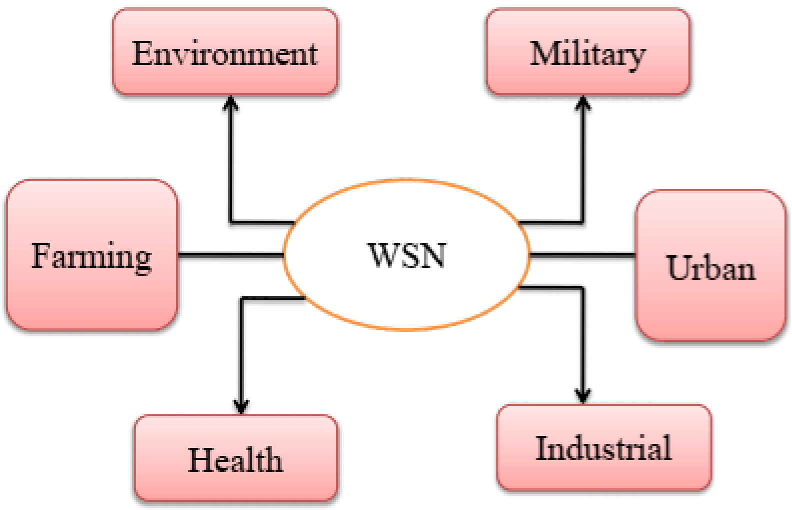



Figure 2.8Applications of WSN [84]

During the previous decade, technology advanced at a dramatic rate. By accessing the internet at low cost, sensor-enabled smart devices become a reality.

### 2.5 Internet of Things

The internet of things (IoT) is a platform that helps all of your devices to connect to the internet and allows them to communicate with one another. It is a vast network of interconnected gadgets that gather and share data information about how they are utilized and the settings in which they operate. In the IoT, any device having built-in sensors and the ability to gather and distribute data across a network without operator interaction qualifies as a "Thing". This technology in the object allows it to interact with internal states as well as the external world, which aids in decision-making. IoT technology may be used in a variety of ways. It depends on the scenario and the location of the gadgets. Network range, network bandwidth, power consumption, interoperability, intermittent connection, and security are some of the variables that influence network type selection. Ethernet cable is used to connect to a wired network. There is no denying that technology has advanced at a breakneck pace during the previous decade. On the other hand, we require Internet connectivity in every region since it provides a vast amount of real-time data. Furthermore, certain settings, such as social media, are entirely online, with all data stored in the IoT Cloud. The new phrases and idioms such as "information in the Cloud" have emerged as the Internet of Things (IoT) [100-103]. IoT has made it simple to connect the inside and outside of the globe due to many sources such as web technology, RFID sensors, and so on. According to some authors 25 billions of things is connected to IoT in coming years [104]. We can observe how the data is gathered and processed for various applications [98], Insight into the business world [105], IoT [106]. From various viewpoints, IoT refers to "a future where things can automatically communicate with computers and each other to deliver services to the advantage of humankind" from the perspective of services supplied by things [43][44]. Data is handled differently in IoT and conventional Internet contexts, as demonstrated in Figure 2.9. Humans are the primary data producers and consumers on the Internet of Computers.

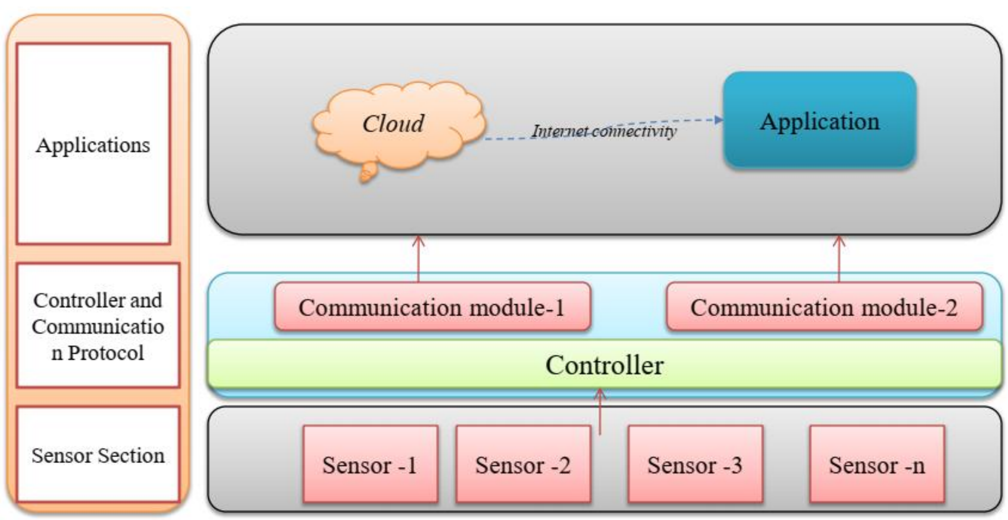



Figure 2.9 Illustration of data acquisition equipment in IoT [98]

IoT recently been focused on high-level generic concerns and are scattered [45] [108]. The Internet of Things offers a lot of high-quality applications and has transformed numerous objects into smart gadgets. The improved items would need to have a greater connection and low-power wireless communication methods in the end. Figure.2.10 shows various IoT communication technologies.

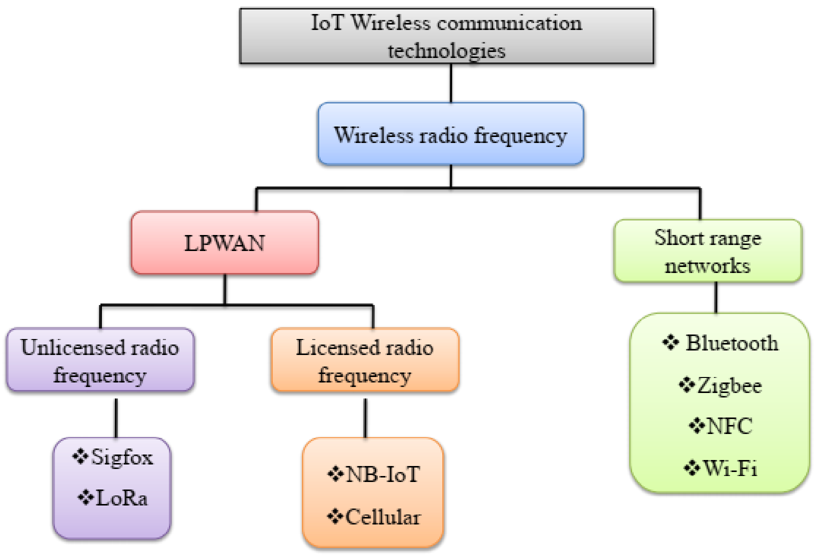



Figure 2.10IoT communication technologies [108]

SigFox is a innovation for remote communication of a wide range of low-essential items, such as sensors and various applications with low-power. It transmits data going as much as 50 kilometers and the data rate is 100 to 600bps with less battery. SigFox bolsters star network topology [109][110]. Cellular can use GSM/3G/4G cell correspondence limits it can give a reliable quick system to the web .with high power. Cell topology depends upon various based innovations [111]. LoRa is along rage communication. The spread spectrum approach is used in LoRa, which is a communication protocol [112]. Messages sent using specific spreading components can also be received by LoRa base stations at the same time. Unlicensed ISM 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia are used in this protocol[113][114]. LoRa provides bi-directional connectivity up to 15 km with a data rate of 50 kbps [115]. Figure.6 gives the architecture of LoRa WAN. Semtech received a patent for the LoRa physical layer in 2014 [116].

With only 30 gateways, they were able to design network coverage for a 100-square-kilometer metropolis, in the same region; this is half the number of access points now required for mobile network installations [112]. In this study, the functioning of LoraWAN in an inside environment, power consumption and radio coverage was examined [118][119]. Another author published another LoraWAN coverage research [120]. Based on real measures, data transmission rates of 80 % for 5 km and 60 % for 5 to 10 km from the gateway are obtained open sea, which is highly encouraging. They simulate the LoRa technology propagation channel based on these real-world data [121]. Decreasing inter-network interference and improving transmission rate are the use of directional antennas and the use of several base stations [121] investigates the influence of these two techniques on reducing inter-network interference in LoraWAN. Narrow Band IoT innovation exists together with GSM and LTE with bandwidth of 200 kHz. Nearly 10 years of battery life can be achieved by transmitting 200bytes of data [122]. The connection is the most crucial part of the IoT paradigm, similar to how modulation schemes allow us to connect to smart gadgets and enjoy affordable solutions. Furthermore, these technologies make use of short-distance communication extremely with low power.

Zigbee protocol is a standard wireless network for the needs of low-cost, low-power IoT applications. It operates on the IEEE802.15.4 standards. Moreover, the topologies for the Zigbee network are like tree, mesh, and star network topology [123-125]. One of the gadgets that play a vital part in WSN is Zigbee. For individual zone organization, Zigbee is a remote low data transmission rates, vitality productivity, the device to device communication, and secure communication are all advantages of Zigbee. Zigbee was designed to provide fast data throughput while using minimal electricity. Low-force Zigbee transmission separations are limited to 100 meters [126]. This technology was created by the Zigbee Alliance [127].The technology is a low-power wireless communication standard protocol using radiofrequency ranges of 2.4 GHz, 915 MHz, and 868 MHz with a 250 kbps transmission rate. The Zigbee devices can run on batteries for a long time with low power. Figure 2.11 shows the Zigbee protocol stack.

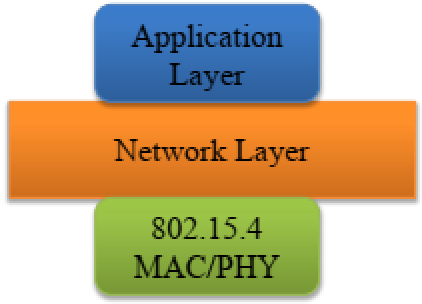



Figure 2.11 Zigbee Protocol stack [123]

NFC is an extremely short-range wireless protocol innovation that empowers the information transmission between gadgets by contacting them together NFC utilizes comparative innovation standards in RFID [128][129]. It is a remote networking innovation based on the 802.11 standard, which is the "radio frequency" expected to broadcast Wi-Fi, it was characterized by Vic Hayes who made the IEEE 802.11 council [130]. Bluetooth is particular in communicating to remotely interface telephones, PCs, and other system devices over short separations by utilizing low power radio. It covers a range of 10 meters with operating frequency. It operated on IEEE 802.15 standards with a 1Mbps data rate [131]. Table 2.3 shows a comparison of various IoT communication protocols.

Table 2.3 Comparison of IoT wireless communication protocols

| **Low Power Wide Area Network (LPWAN)** | | | | | |
|---|---|---|---|---|---|
| Sno | Parameter | SigFox | NB-IoT | LoRa | Cellular |
| 1 | Bandwidth | 100Hz | 200KHz | 125KHz and 250KHz | GSM 850 MHz and 1900 MHz |
| 2 | Data rate | 100bps | 200kbps | 50kbps | Up to 100 Mb/s |
| 3 | Range | Up to 40 | Up to 10Km | Up to 15Km | 0.8 km to 8 |

| | | | | | |
|---|---|---|---|---|---|
| | | Km | | | km |
| 4 | Bi-directional | Limited | yes | yes | Yes |
| 5 | Frequency | 433, 858,915 MHz | Licensed LTE frequency | 433, 858,915 MHz | 600 MHz to 2.5GHz |
| 6 | Immune to interference | High | Low | Very high | High |
| **Short range networks** | | | | | |
| SNo | Parameter | Bluetooth | Zigbee | NFC | Wi-Fi |
| 1 | Bandwidth | 2400-2483.5 MHz | 2.4GHz | 13.56 MHz | 22MHz |
| 2 | Data rate | 0.7-2.1Mbps | 20kbps to 250kbps | 106 kbit/s to 424 kbit/s | 54 Mbps |
| 3 | Range | Up to 100 cm | Up to 100 mts | 10 cm | 150 feet indoors and 300 feet outdoors |
| 4 | Bi-directional | Yes | Yes | Yes | No |
| 5 | Frequency | ISM 2.4GHz | ISM 2.4GHz | 13.56 MHz | 2.4GHz |
| 8 | Power Consumption | Medium | Medium | Approx 40 mA | 2 to 20 watts |

## 2.6 Oil Pipeline Management

Pipeline leaks and bursts, offshore gas, and oil pipelines have become a hazard for the environment. Breakdown maintenance is both time and money-consuming. One of the important methods for researchers is to maintain pipeline operations depending on risk.

The suggested technique aids researchers and pipeline operators in dynamically maintaining pipeline health. Specific maintenance and inspection should be performed by the severity and likelihood of failure [170]. Some of the researchers in [11] Real-time pipeline leak detection systems have a lower cost-effective rate and a lower false alarm rate. Different pipeline leak detection algorithms are examined in this study, and the system's performance is given. In [171] the collapse of an oil and gas pipeline was investigated using a fault tree analysis in this article. Fifty-five minimal cut sets were produced via qualitative analysis. Quantitative analysis was used to determine the top event of failure likelihood. We offer fuzzy set theories to overcome traditional techniques for evaluating the likelihood of events. For example, the total length of subsea pipes is now above 2000 kilometers. However, during the 1990s, several subsea pipeline incidents have occurred, resulting in a variety of damages owing to a variety of factors, including pipeline operation exceeding design capacity, vessels anchoring, dragnet, washing out, error operation, severe bumping, corrosion, and so on. Based on CNOOC's pipeline repair operations and the features of pipeline damage, this article introduces subsea pipeline repair techniques and procedures, as well as some recommendations [172].

Tiny unmanned aerial system (UAS) aircraft with dynamic vertical takeoff and landing (VTOL) capabilities and docking platforms for accommodating the UAS aircraft are used for long-range monitoring and surveillance of facilities and infrastructure of various pipelines of oil, water, gas, and power lines. The UAS may undertake continuous monitoring and surveillance of facilities utilizing one or more embodiments while flying autonomously along a pre-programmed flight route [173]. The UAS aircraft may be equipped with an integrated gas collection and analyzer unit, as well as the ability to transfer gathered data and analyzer information from the aircraft to docking stations. In [174] as the world's infrastructure grows, health monitoring of structures becomes increasingly vital. Corrosion in oil and gas pipelines is being caused by certain infrastructure. Because high-pressure lines might burst during testing owing to deterioration, causing harm to inspectors, the ultrasonic bulk wave has proven timeconsuming and risky. Ultrasonic tomography can be used to rebuild pipeline infrastructure. 16 tiny piezoelectric discs are connected to a 100 mm schedule 40 steel pipe elbow in this work as an example. Before and after each of the multiple phases of damage, signals are stimulated and collected from each transducer in the array. The current state of gas and oil cleaning technology pipelining at home and abroad, the type of pipeline pig, the basis for type selection, quality control of pigging operations, the pigging cycle, control and prediction of pig speed, pig tracking and location, and determination of pigging operation safety area, as well as foreign advanced experience of pipeline cleaning technology are all discussed. Some issues in household pigging technology are addressed, such as the unsatisfactory cleaning effect and the absence of consistent standards, and a benchmark for increasing the quality of residential pipe cleaning technology is established [142]. In corrosion monitoring, constructing appropriate corrosion devices for acquiring localized corrosion and metals decline data from difficult underground pipeline locations is a challenge. This article provides an overview of current developments in this field as well as a brief assessment of future potential [175].

WSN-based systems are neither inherently incompatible nor homogeneous. They don't have a coordinated communication and transparency strategy across areas and procedures. SCADA systems reduce the number of complicated setups and device programming [176]. WSN technology is widely regarded as a superior technology for oil and gas infrastructure maintenance, particularly pipeline maintenance. In maintenance, data may be gathered by various sensor nodes and communicated through GPRS, modems, and other means. Collecting these data requires low cost and lengthy data transmission latency. This article explains how to collect data from WSN sensor nodes using an algorithm and data fusion technologies. Furthermore, the suggested technique significantly improves data gathering in the pipeline. A vast network of gas and oil pipelines transports crude oil over large distances. They continue to monitor for leak detection, corrosion, and other losses. Hazardous circumstances should be avoided at all costs. This study offers a gas and oil pipeline monitoring reliability model based on wireless sensors and networks (WSN). The method used is quite dependable for long-distance travel. These models provide a better understanding of component and system dependability [177]. Adhoc sensor networks are a new technology that is rapidly gaining traction in the industrial world. Electronic components are improving memory, speed, networking, and communication these days and more useful in military, agricultural, and space research, among other fields. This article provides a quick overview of oil, water, and gas pipeline monitoring and control. Routing protocols and data working are included in the model, which is utilized to transfer data across vast distances [178]. The major goal of this study is to calculate the likelihood of aged pipes failing due to corrosion. Oil pipeline dependability is assessed using the fuzzy artificial neural network (FANN) technique. We have a simulation-based probabilistic reliability framework with eight pipe characteristics as input variables for evaluating pipeline reliability and the output variable is the chance of failure [179].

The production and monitoring of water, gas, and oil pipelines utilizing wireless sensors and networks are presented in this article. Routing protocols and networking frames provide a novel hierarchical addressing system for wireless sensor networks with linear structures. Maintenance costs and energy requirements are both decreased as a result of the linear form of the installation. Additionally, it extends life and improves communication efficiency [180]. In [181] article provides a complete model for gas and oil pipeline repair options for long-term service. For calculating maintenance and economic factors, as well as operating costs, this model employs fuzzy and Monte Carlo simulation. This study [182] examines and predicts a variety of variables, including corrosion, for an offshore gas and oil pipeline in Qatar. In Qatar, an artificial neural network model is being utilized to collect data from offshore gas and oil pipelines. This logic has a success rate of over 97 percent in predicting data from pipelines. Engineers can use this model to inspect and restore pipeline characteristics. A Bayesian belief network is used in this article to represent the breakdown of an oil and gas pipeline. The FBBN model is well-suited to accidental conditions since it is both a probability model and a representation of uncertain knowledge [183]. Overload, damage, constructional problems, job quality, and improper installation are all proposed as important reasons for pipeline failure in this model. Table 2.4 below shows a comparative study of IoT-based pipeline monitoring approaches.

Table 2.4Study of Existing methodologies of Oil pipeline monitoring

| Reference | Title of the paper | Description |
|---|---|---|
| [14] | Novel vibration-based technique for detecting water pipeline leakage. | Author focus on water leak in 76 mm diameter polyvinyl chloride pipe using vibration technique. |
| [20] | Recent advances in pipeline monitoring and oil leakage detection technologies: Principles and approaches. | In this study, A review made on the oil pipeline monitoring methods and spill detection approaches. |
| [33] | The Intelligent Crude Oil Anti-theft System Based on IoT Under Different Scenarios. | This paper present the oil theft monitoring from the pipe using supervisory control and data acquisition. |
| [48] | A service-oriented middleware for building collaborative UAVs. | This proposed cloud offers different opportunities in UAVs applications development and deployment. |
| [55] | Real time automatic object detection by using template matching for protecting pipelines. | The work has been designed and developed to enhance drone's flight capabilities as well as reduce a risk for the personnel in drive surveying and lessen down the working time. |

| | | |
|---|---|---|
| [59] | Modeling and analysis of a catastrophic oil spill and vapor cloud explosion in a confined space upon oil pipeline leaking. | A numerical model was developed to estimate the consequence of the explosion based on volatilization testing results. |
| [60] | Unmanned Aerial Systems for the Oil and Gas Industry: Overview, Applications and Challenges. | The objective of this review article is to highlight the usability of UAS for the oil and gas industry, focusing mainly on UAS applications and the opportunities and challenges of UAS deployment. |
| [132] | Decision analysis framework for risk management of crude oil pipeline system. | Leak and corrosion detection using Analytic hierarchy process (AHP) which calculates frequency of failures with comparison of previous events |
| [133] | Applications of wireless sensor networks in the oil, gas and resources industries. | Leaks, corrosion, Reservoir status in real time monitoring and reducing operating cost with short range communication. |
| [134] | Oil and gas pipeline failure prediction system using long range ultrasonic transducers and Euclidean-Support Vector Machines classification approach. | Leaks and corrosion with long range ultrasonic sensors and classification of failures using Euclidean-SVM & LRUT methods. |
| [22] | Small unmanned airborne systems to support oil and gas pipeline monitoring and mapping. | Reviews of Oil pipeline are monitored using Unmanned aerial Vehicles. |

| | | |
|---|---|---|
| [135] | Hierarchical leak detection and localization method in natural gas pipeline monitoring sensor networks. | Leak detection and localization using wavelet transform technology. |
| [136] | Leak detection monitoring system of long distance oil pipeline based on dynamic pressure transmitter. | Leak detection monitoring system (LDMS) & Dynamic pressure transmitter (DTP) with various pressure sensors placed on the pipe. |
| [137] | Focal design issues affecting the deployment of wireless sensor networks for pipeline monitoring. | Design issues affecting pipeline monitoring. |
| [138] | Advances in asset management techniques: An overview of corrosion mechanisms and mitigation strategies for oil and gas pipelines. | In line and Online Corrosion detection<br>with corrosion risk Assessment technique for corrosion monitoring of the pipeline. |
| [139] | Oil and gas process monitoring through wireless sensor networks: A survey | Monitoring oil and gas pipeline methods using WSN. |
| [140] | Main pipelines corrosion monitoring device. | Corrosion monitoring of pipeline using pigging devices. |
| [141] | An overview of recent progresses in acquiring, visualizing and interpreting pipeline corrosion monitoring data. | Underground pipeline corrosion detection using ultrasonic transducers and it is static monitoring |

| | | |
|---|---|---|
| [142] | Multi resolution change analysis framework for post disaster assessment of natural gas pipeline risk | This paper presents a multi-resolution change analysis approach for detecting emerging threats to natural gas pipeline systems after a natural disaster. |
| [143] | The role of UAS in digital era governance. A systematic literature review. | The main research objective of this study was to evaluate the applicability of geographic information system (GIS) tools to the implementation of sustainable development principles in rural areas. |
| [23] | SimpliMote: A wireless sensor network monitoring platform for oil and gas pipelines. | Leak detection and actuation with sensor mote. Low latency and keeping network alive all time. |
| [144] | Experimental study on pipeline internal corrosion based on a new kind of electrical resistance sensor. | Low cost and metal loss measurement detection with Electrical resistance sensor (RPERS). |
| [145] | An infrared non-contact framework for monitoring the liquid levels in oil pipelines. | Liquid level measurement in side pipeline using infrared thermal sensor. |
| [146] | Optical sensing and monitoring architecture for pipelines using optical heterodyning and FBG filter. | Optical heterodyning and FBG filter method to detect the Leaks and Pressure of the pipeline. |
| [147] | Remote pipeline monitoring using wireless sensor networks. | Leak detection using tiny sensors placed on the pipeline using WSN. |

| | | |
|---|---|---|
| [148] | Node placement approaches for pipelines monitoring: simulation and experimental analysis. | Node placement approach at the entire length of the pipeline to measure the pressure variation of the pipeline at various nodes. |
| [149] | Inter Integrated WSN for Crude Oil Pipeline Monitoring. | Crude oil pipeline monitoring using WSN and QOS secured message queuing telemetry transport. |
| [150] | Edge analytics for anomaly detection in water networks by an Arduino101- based WSN. | Water pipeline network monitoring using edge analytics, by placing sensor nodes on the pipeline and transferring data to previous node. Whole data no need to send server all the time. |
| [153] | Low-cost, open source based SCADA system design using thinger. | These authors focus on the usage of Supervisory control and data acquisition (SCADA) system for data acquisition. |
| [154] | Network challenges for cyber physical systems with tiny wireless devices: A case study on reliable pipeline condition monitoring. | Pipeline condition monitoring using small wireless sensor motes and data communication using cyber physical systems (CPS). |
| [155] | Sensors for Fluid Leak Detection. | Ultra sonic sensor used to detect the leaks of fluid. |
| [156] | Wireless sensor network modeling and deployment challenges in oil and gas refinery plants. | This author address on quality of service from WSN in oil and gas refinery plants. |

| | | |
|---|---|---|
| [157] | Ultra-wide band sensor networks in oil and gas explorations. | Amount of data collected in a survey using seismic acquisition systems for Upstream, Midstream and downstream sectors for analysis. |
| [158] | Analysis and Comparison of Long-Distance Pipeline Failures. | Long distance pipeline failures analyzed with corrosion detection |
| [160] | Low-Power wide-area networks For sustainable WSN. | In this study, Author focus on leak detection using vibrations of the pipeline using accelerometer sensors |

## 2.7 Research Gap

- Low cost monitoring system needs to be explored
- Development of low complex integrated system to monitor all critical parameters is essential.
- Smart corrosion monitoring and detection methods are necessary
- Implementation of long distance communication with IoT network for efficient pipeline parameters monitoring and data management needs to be studied.
- IoT enabled drones can be impart for real time data capturing.

## 2.8 Chapter Summary

This chapter presents the related works in oil pipeline management. It contains a review of the literature on oil industry, pipes, Wireless Sensor Networks, the Internet of Things. We also looked at oil pipeline concerns across the world, as well as monitoring and leak localization methods for oil pipelines in various studies to see what the benefits and drawbacks were. The specifications of several long and short range IoT communication protocols are examined. The research gap is identified after a study of several research articles.

# CHAPTER-3

# SYSTEM ARCHITECTURE

This chapter focus on the system architecture of the oil pipeline is presented. Initially, the architecture's system description was developed, which included sub-modules of the architecture with their block diagrams and interfacing, PCB design, circuit, Proteus simulations, and customized hardware boards. Moreover, the methodology of the sensor nodes is addressed and various sensor components specifications are discussed.

## 3.1 System Architecture

The Architecture is presented for implementing oil pipeline monitoring using LoRa and IoT technology. The system architecture comprises five sub-modules namely Sensor node-1, sensor node-2, Safety operation controller, gateway, and drone yard as shown in figure 3.1. This describes the data flow between the sensor nodes, gateway, and IoT cloud. Furthermore, this design assists in the implementation of an IoT-based oil pipeline monitoring system in areas where internet connectivity is minimal and difficult. Moreover, 2.4 GHz RF and LoRa communication protocols play a prominent role in transfer data between sensor nodes and gateway. The data acquired from the fields of sensor nodes of the pipeline are communicated to the gateway via LoRa communication that enhances reliable connectivity between sensor nodes and gateway. However, if any abnormal issues or third-party damages are detected from sensor nodes of the pipeline, an alert is communicated to the safe operation controller (SOC) and Drone yard via a 2.4GHz RF module from sensor nodes. After receiving an alert SOC plays an eminent role in activating hooter and alert pipeline field workers. Moreover, the Drone yard activates the drone and starts inspecting the pipeline for finding and locating leaks of the pipeline. While inspecting the status of the drone is communicated to the gateway via the LoRa module and visuals and location is shared to a web server. Here drone is utilized for on-demand visual communication. LoRa is used by sensor nodes to send sensor data to the gateway. The gateway takes sensory data from the sensor nodes via LoRa and transfers it to the IoT cloud server via the internet. Gateway is embedded with LoRa and a Wi-Fi module

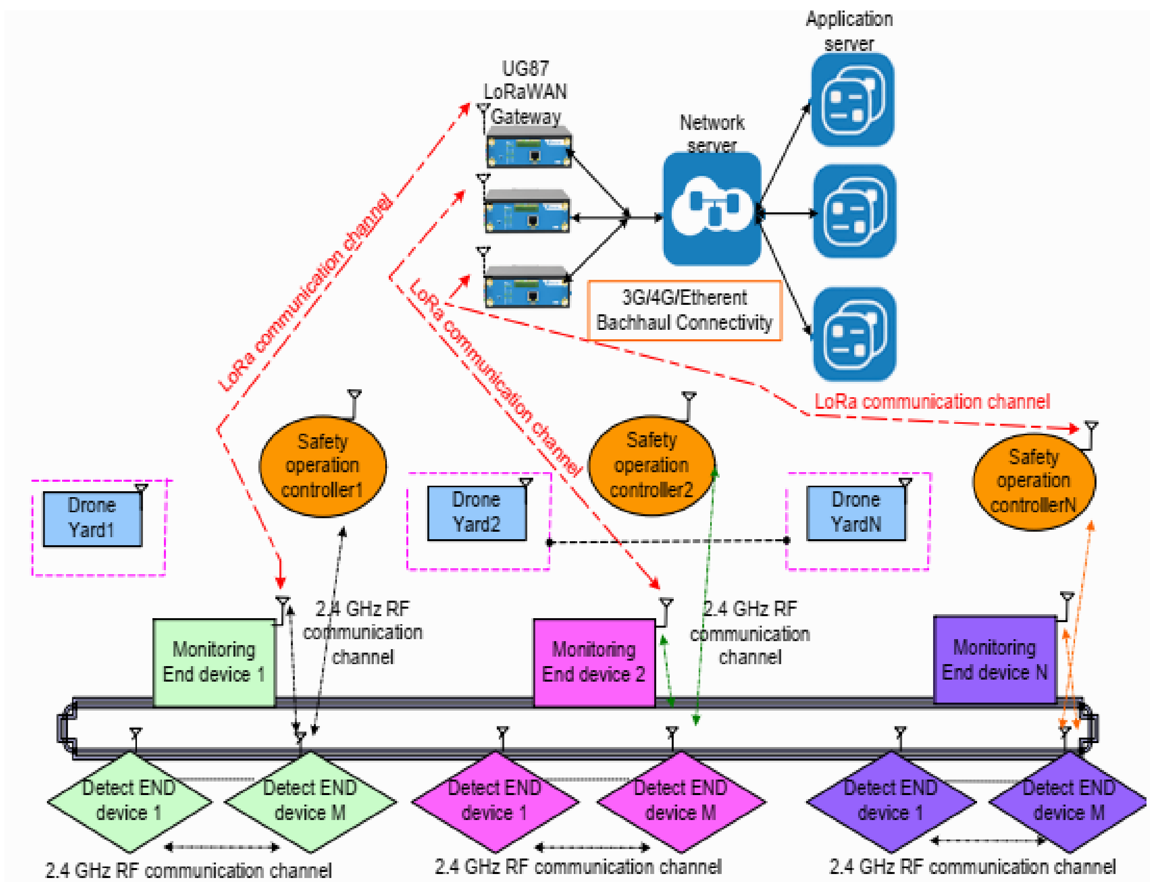



Figure 3.1 System Architecture for monitoring pipeline parameters in the oil field.

### 3.2 Sensor Node-1

This sensor node monitors the pipeline's parameters. The parameters to be monitored are the humidity, oil temperature, flow rate, and pressure of the pipeline. All the sensor data is collected by the controller and send to the gateway via LoRa communication. Moreover, if any abnormal issues are found in the pipeline monitoring the alert is sent to the safety operation controller (SOC) and drone yard and activate both. The block diagram of monitoring end device is shown in figure 3.2.

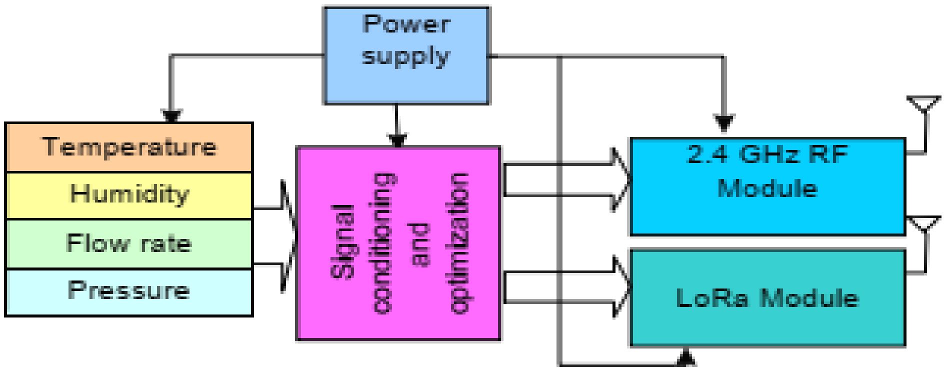



Figure 3.2 Block diagram of Sensor node-1

The sensor node-1 is simulated in proteus simulation environment with piezo electric pressure sensor, temperature sensor and virtual terminal interfacing with ATMeag328p microcontroller before designing of customized hardware node as shown in figure 3.3. Here the solar power is used to power up the sensor node and sensor output data is displayed in virtual terminal.

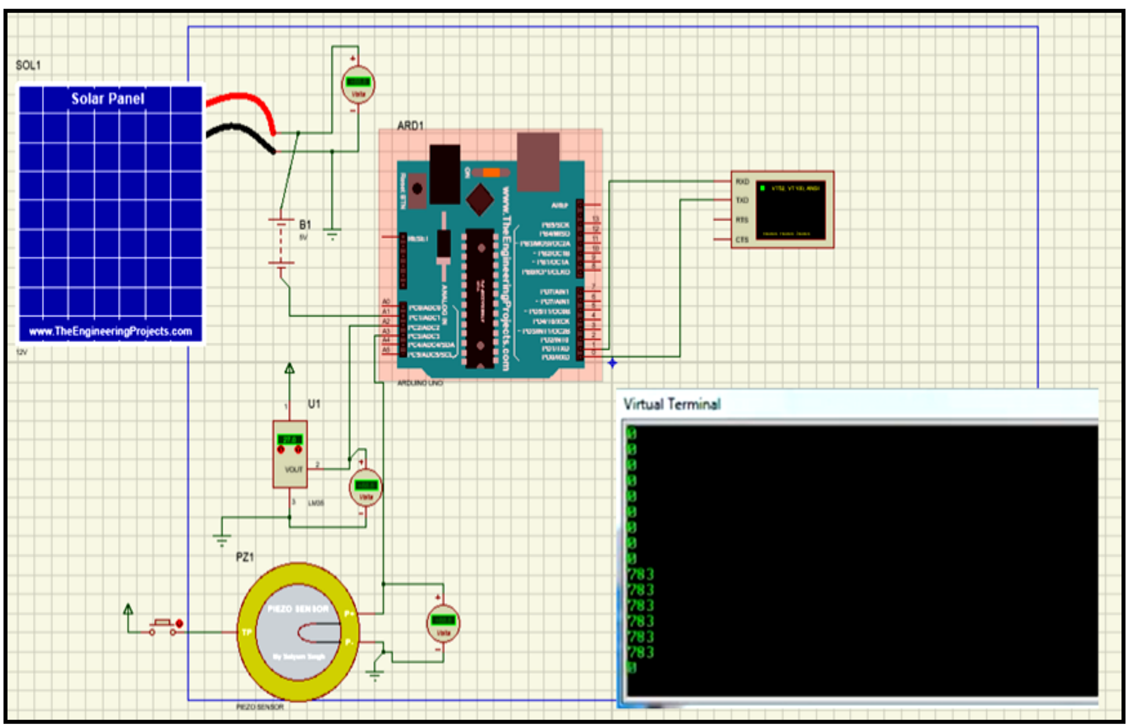



Figure 3.3 Proteus simulations of Sensor node-1

The sensor node's circuit and PCB design are shown in the figure. 3.4and figure 3.5 ATMEGA328 is an 8-bit microcontroller that making it ideal for low-cost IoT and WSN applications. The controller's operating voltage is between 1.8 and 5 volts. The sensor mote's power supply is made up of a bridge rectifier and an AC step-down transformer. The voltage regulators LM7812 and LM7805 are included in the sensor mote to satisfy the different power supplies of 12 V and 5V. SEMTECH developed the SX1278 LoRa module, which is a transceiver radio frequency (RF) module. This module has a frequency range of 137MHz to 525MHz.The maximum transmission data rate of LoRa is 300kbps.The nRF24L01 transceiver module transmits data using GFSK modulation and operates in the band 2.4 GHz with data rate of 250kbps. The module's working voltage ranges from 1.9 to 3.6V.

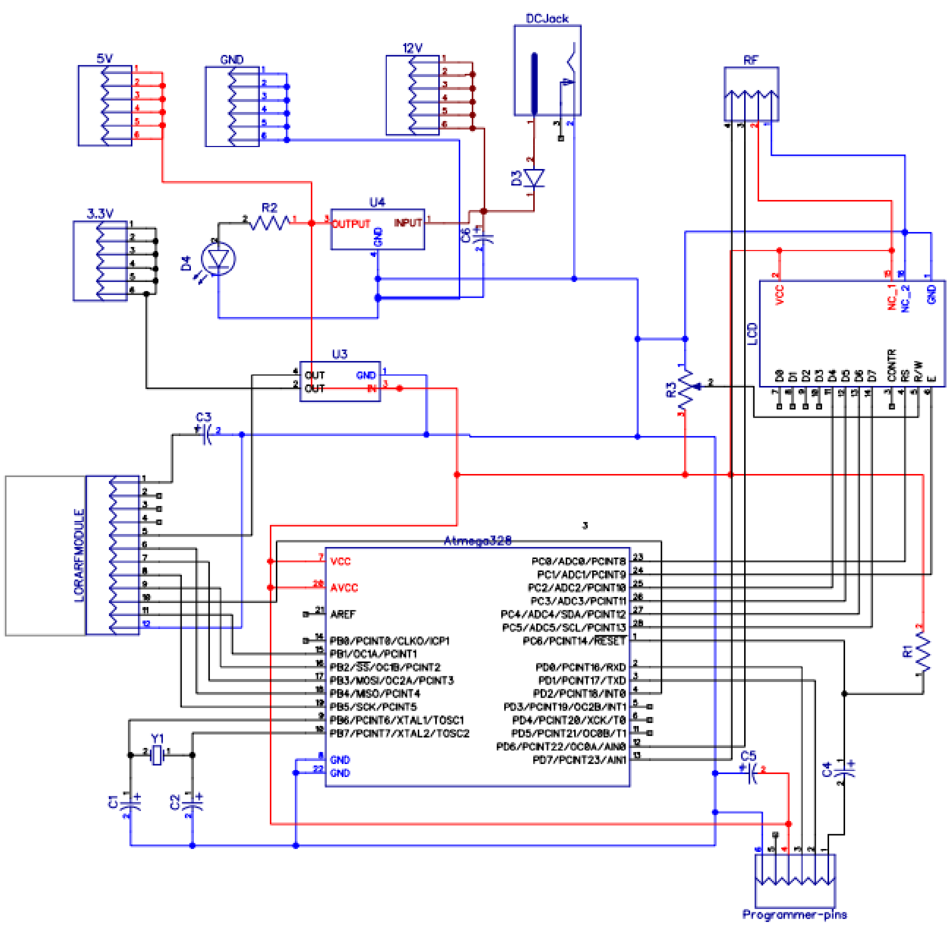



Figure 3.4 Circuit design of sensor node-1

The circuit connections of monitoring section are as follows

- The power rail pins of +12V, 5V, and 3.3V are on board to give the supply to sensors and actuators.
- The MOSI, MISO, SCK, GND, Vcc and RESET pins of the Lora modem are connected with 17,18,19, GND, +5V and RESET pins of customized Atmega328 board.
- The Zigbee is connected to pin-12,13 of the customized atmega328 board and Vcc and GND are connected to +3.3v and GND.
- The Vcc, GND, and OUT pins of the temperature sensor are connected with +3.3V, GND, and PC0 pins of the customized atmega328 board.
- The Vcc, GND, and OUT pins of the Pressure sensor are connected with +5V, GND, and PC3 pins of the customized atmega328 board.
- The Vcc, GND, and OUT pins of the Flow sensor are connected with +5V, GND, and PC4 pins of the customized atmega328 board.

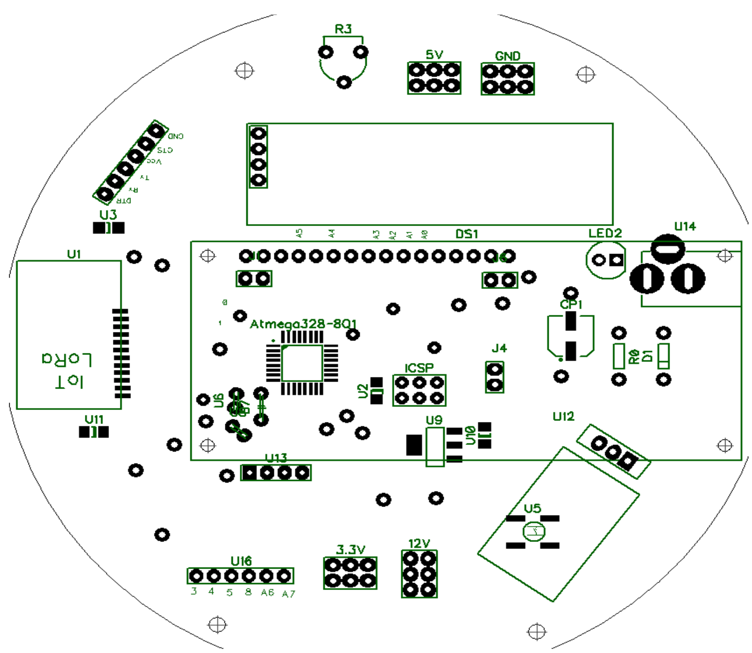



Figure 3.5 PCB Layout of Sensor node-1

The nRF 24L01 transceiver interfaced with an atmega328p microcontroller for data transmission to the SOC and drone yard. The MISO, MOSI, ground, and SCLK pins f the LoRa SX1278 module are used to communicate with the ATMEGA328. There are various digital and analog pins on the sensor array. The LM7812 regulator is included in the board and regulates the output voltage to 12 volts. For interfacing IoT sensors, the input voltage can be regulated to +3.3v and +5.5v. The customized hardware node is illustrated in figure.3.6.

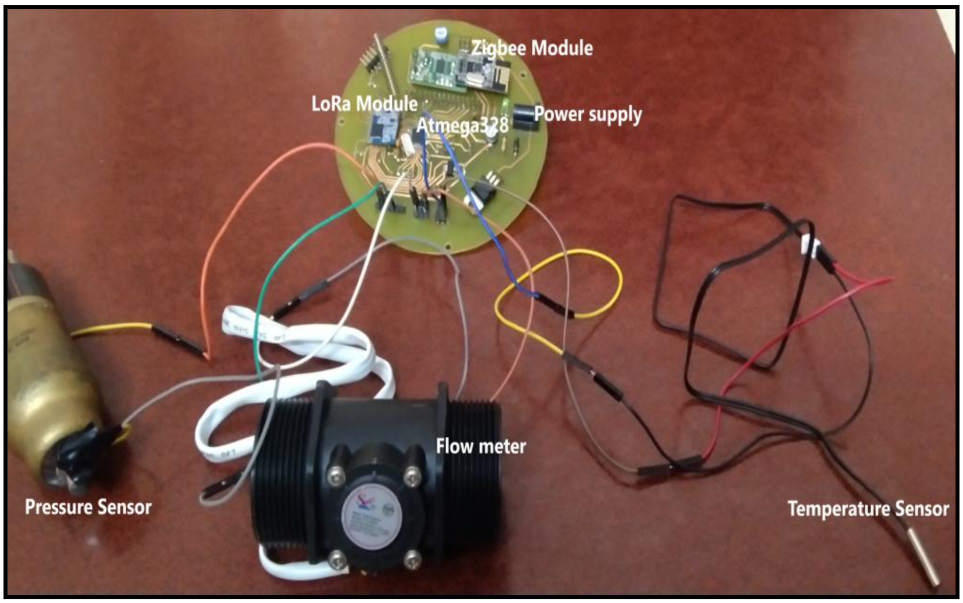



Figure 3.6 Customized hardware of sensor node-1

The sensor data collection is facilitated significantly by the sensor node-1 of the pipeline and communicates it to the end-user. The controller collects all sensor data and sends it to the gateway through the LoRa connection. Furthermore, if any anomalous issues are discovered during pipeline monitoring, an alert is transmitted to the safety operation controller (SOC) and the drone yard, causing both to be activated. Figure.3.7 gives the methodology for monitoring end device.

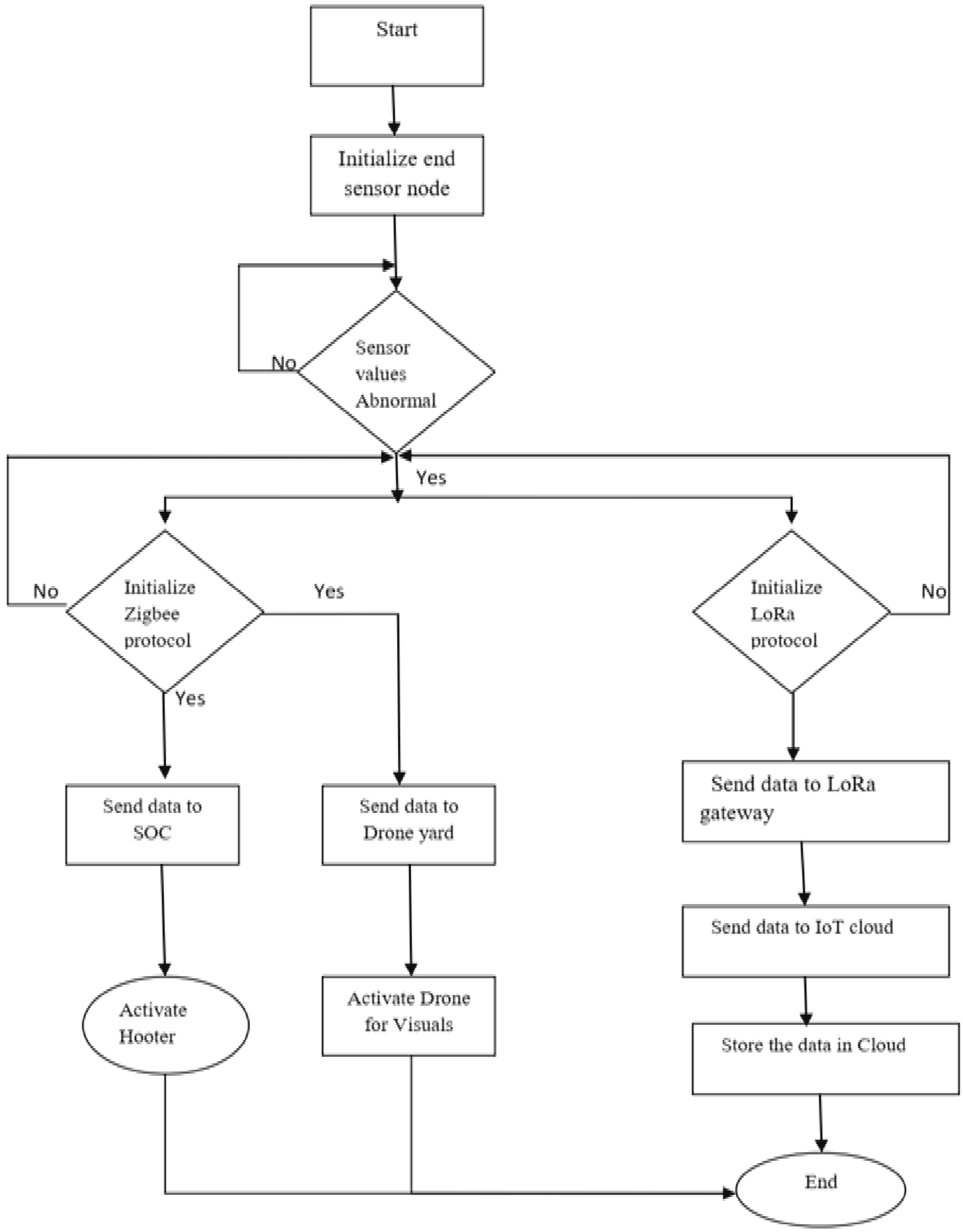



Figure 3.7 Methodology for Sensor node-1

### 3.1.2 Sensor node-2

This sensor node is important in detecting a pipeline's critical parameters. This sensor node detects various parameters like vibrations, whenever third-party damages have occurred on the pipeline. If methane gas is detected caused due to fire, the smoke detection sensor is activated. Moreover, acoustic waves occurred due to pipeline leaks acoustic sensor is used to detect those signals. All parameter data is collected by the controller and sent to the monitoring end device using 2.4 GHz RF connection. after which the data is transmitted to the gateway through LoRa communication. Furthermore, if any anomalous issues occur, a warning is sent to the SOC to trigger the hooter. Figure.3.8 block diagram of the detection end device.

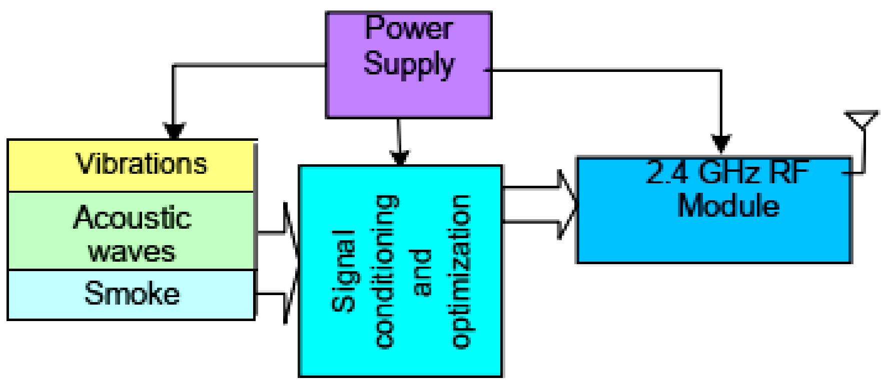



Figure 3.8 Block diagram of Sensor node-2

The proteus simulation environment with a vibration sensor, acoustic sensor, smoke detection sensors interfacing with ATMega microcontroller as shown in figure 3.9. Here the solar power is used to power up the sensor node and output data is displayed in the virtual terminal and LCD. The sensor node's circuit and PCB design are shown in the figure. 3.10 and figure 3.11.ATMEGA328 is an 8-bit microcontroller that is well-suited for low-cost Internet of Things applications. The operating voltage of the controller is between 1.8 and 5 volts. A bridge rectifier and an AC step-down transformer make up the sensor mote's power source. The sensor mote includes the voltage regulators LM7812 and LM7805 to handle the varied power supplies of 12 V and 5V.

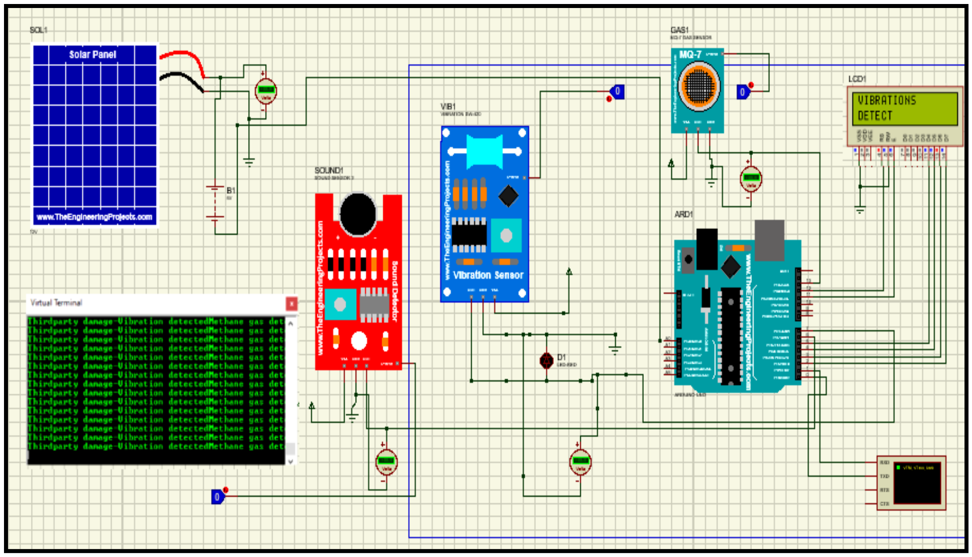


Figure 3.9 Proteus simulations of Sensor node-2

The nRF24L01 transceiver module transmits data using GFSK modulation and operates in the band 2.4 GHz with data rate of 250kbps. The module's working voltage ranges from 1.9 to 3.6V.

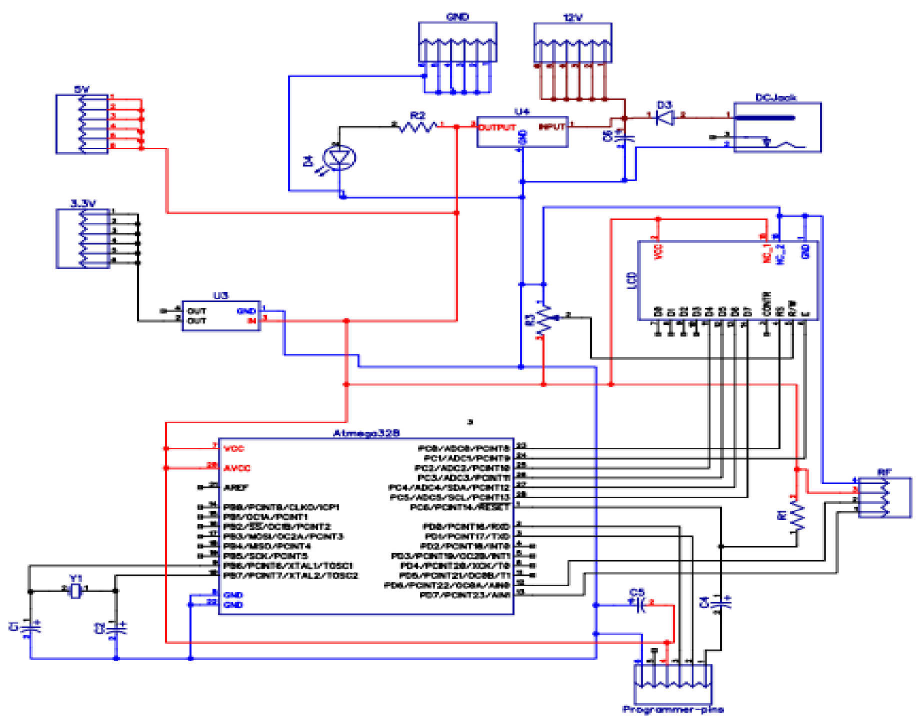


Figure 3.10 Circuit design of Sensor node-2

- The power rail pins of +12V, 5V, and 3.3V are on board to give the supply to sensors and actuators.
- The Zigbee is connected to pin-12, 13 of the customized atmega328 board and Vcc and GND are connected to +3.3v and GND.
- The Vcc, GND, and OUT pins of the vibration sensor are connected with +3.3V, GND, and PC1 pins of the customized atmega328 board.
- The Vcc, GND, and OUT pins of the vibration sensor are connected with +3.3V, GND, and PC0 pins of the customized atmega328 board.
- The Vcc, GND, and OUT pins of the vibration sensor are connected with +3.3V, GND, and PC3 pins of the customized atmega328 board.
- Onboard +12V to +5V convertor is connected to +Vcc and GND pins of the atmega328 microcontroller.

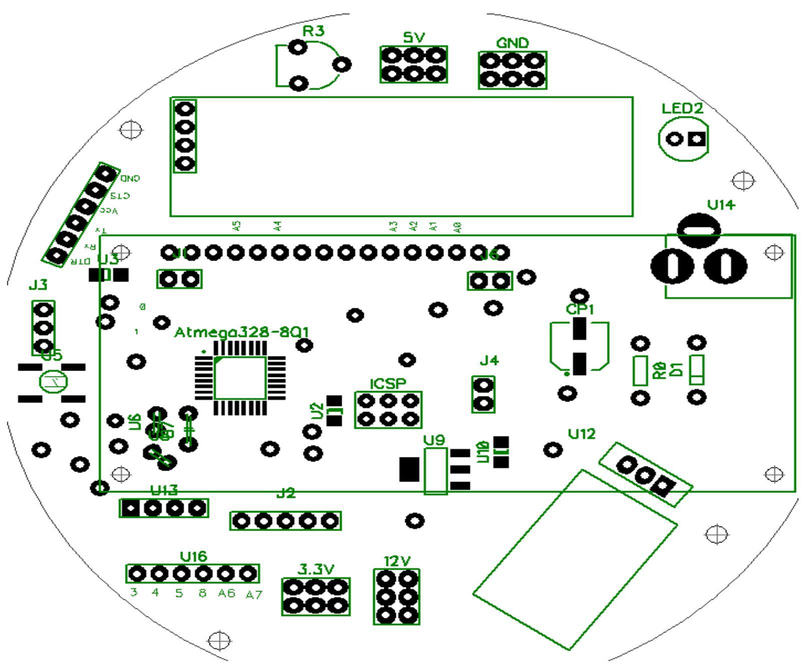



Figure 3.11 PCB Layout of sensor node-2

The nRF 24L01 2.4 GHz RF module is connected to an atmega328p microcontroller, customized hardware node is illustrated in figure 3.12. Digital and analog pins are included in the sensor array. The LM7812 regulator is included in the board and regulates the output voltage to 12 volts. For interfacing IoT sensors, the input voltage can be regulated to +3.3v and +5.5v. The atmega328 microcontroller's +Vcc and GND pins are wired to the onboard +12V to +5V converter.

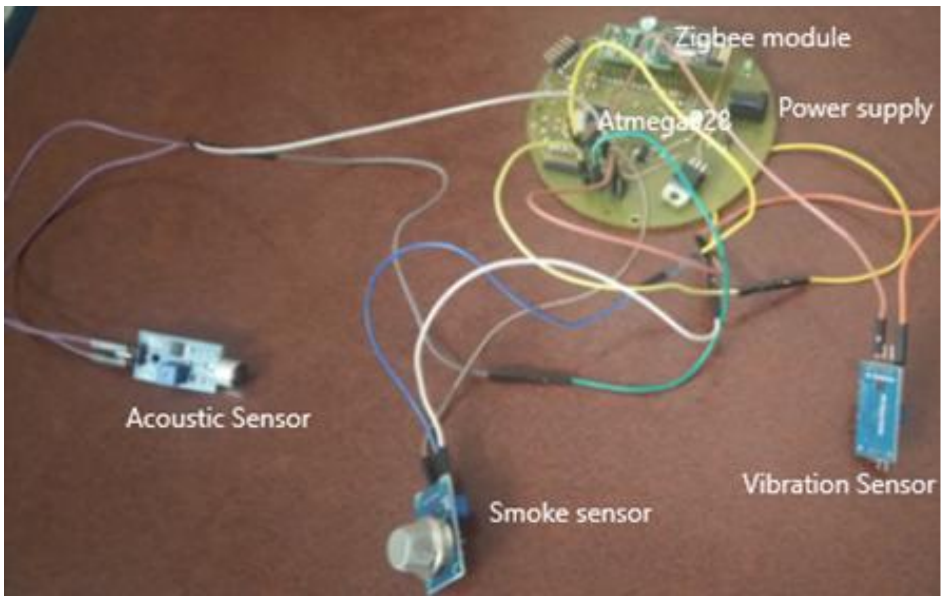



Figure 3.12 Customized hardware of sensor node-2

The sensor data collection is facilitated significantly by the sensor node-2 of the pipeline especially third-party damages and communicate to the sensor node-1. The sensor node-1collects all sensor data and sends it to the gateway through the LoRa connection. Furthermore, if any anomalous issues are discovered during pipeline monitoring, an alert is transmitted to the safety operation controller (SOC) and the drone yard, causing both to be activated. Figure3.13 gives the methodology of the detection end device.

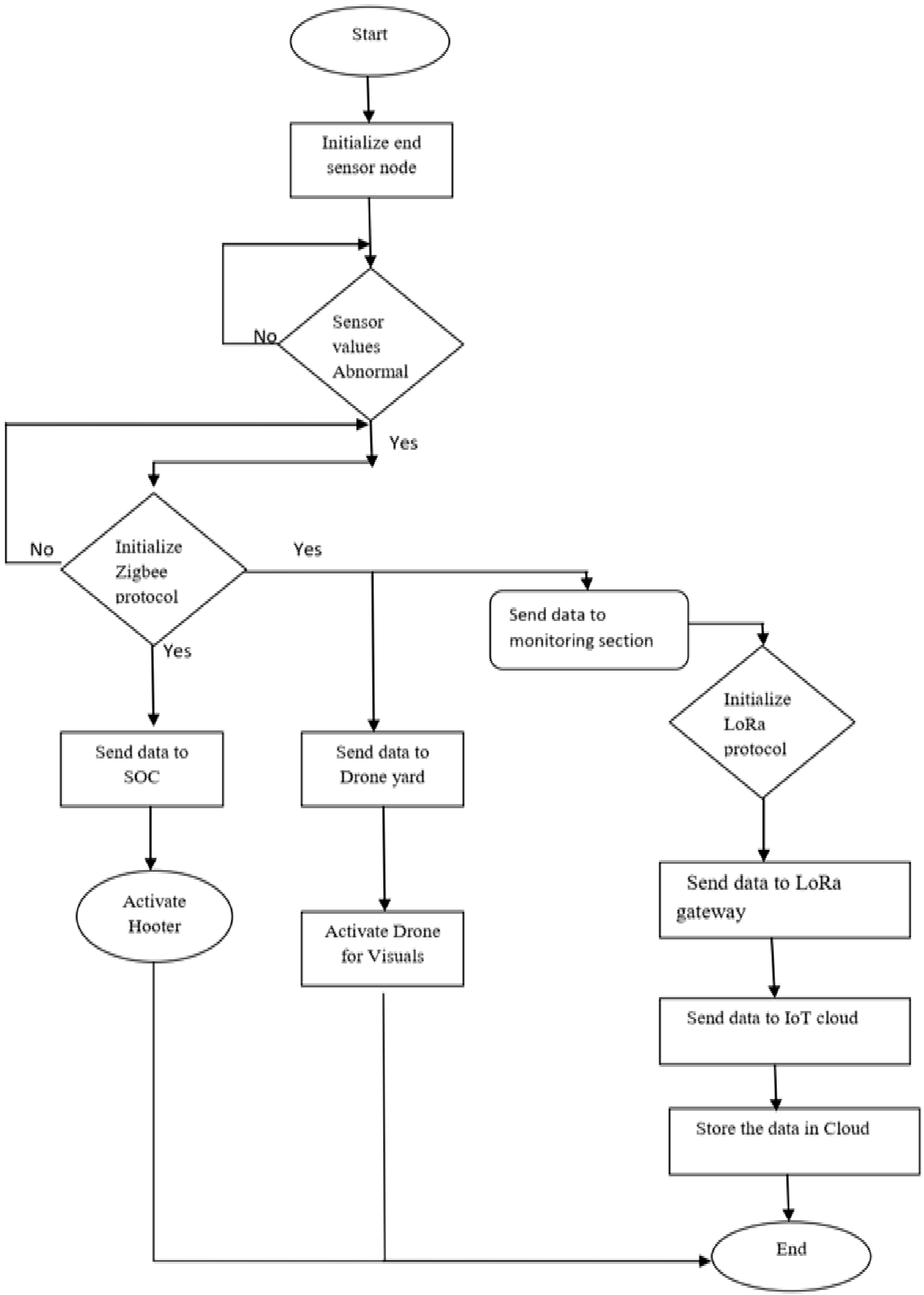



Figure 3.13 Methodology for Sensor node-2

### 3.1.3 Safety Operation Controller

Safety operation controller (SOC) plays a prominent role in alerting field staff and others by activating the hooter when any abnormal issues are found in the monitoring and detection section. The sensor nodes will communicate a signal to SOC via the 2.4 GHz RF modules and hooter is activated. Figure. 3.14 show the SOC block diagram. It comprises a power supply circuit that provides power to the wireless RF controller, hooter driver, and hooter.

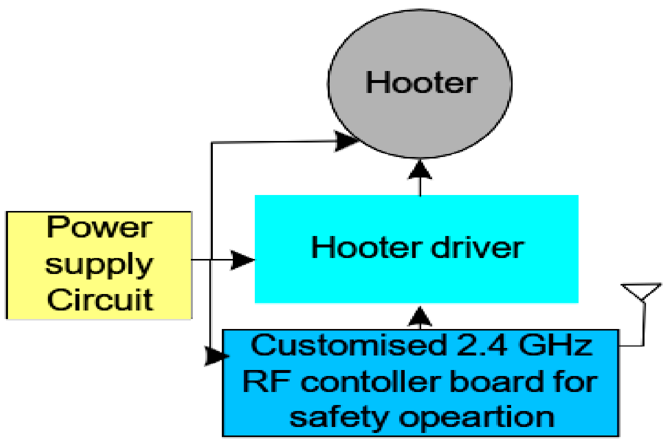



Figure 3.14 Safety operation controller device

The SOC device is simulated in a proteus simulation environment with a hooter and displayed output in oscilloscope as shown in figure 3.15. The simulation of activating the hooter by using a microcontroller and output is displayed in the oscilloscope. Here the microcontroller is interfaced to the hooter and oscilloscope. Moreover, microcontroller is triggered with audio input and generated analog input in the display. The circuit design and PCB design of the safety operation controller (SOC) is shown in the figure. 3.16 and figure 3.17. ATMEGA328 is an 8-bit microcontroller and the operating voltage of the controller is between 1.8 and 5 volts. The relay switch with 1 channel 5v is interfaced with an ATMega microcontroller which is used to activate the hooter. A bridge rectifier and an AC step-down transformer make up the sensor mote's power source. The sensor node includes the voltage regulators LM7812 and LM7805 to handle the varied power supplies of 12 V and 5V.

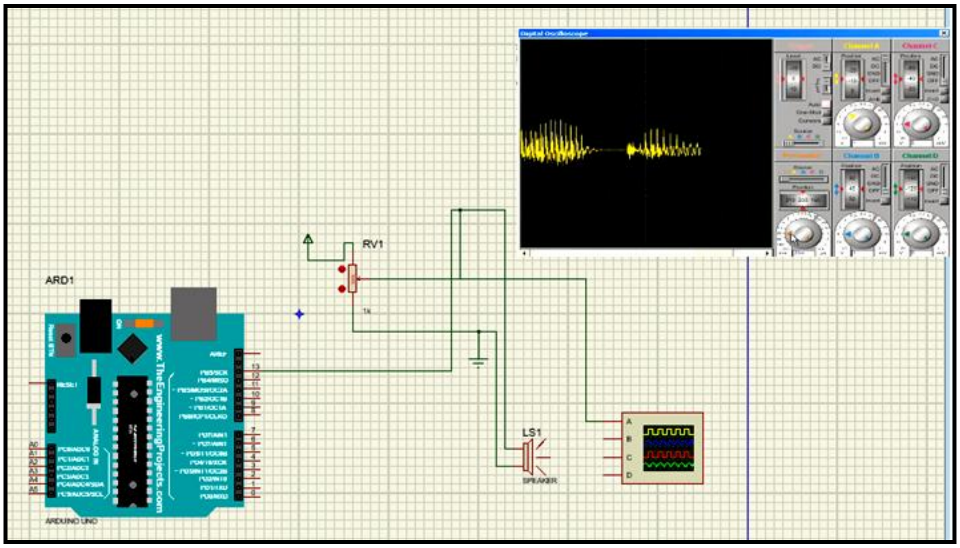



Figure 3.15 Proteus simulation of SOC

The nRF24L01 transceiver module transmits data using GFSK modulation and operates in the band 2.4 GHz with data rate of 250kbps. The module's working voltage ranges from 1.9 to 3.6V.

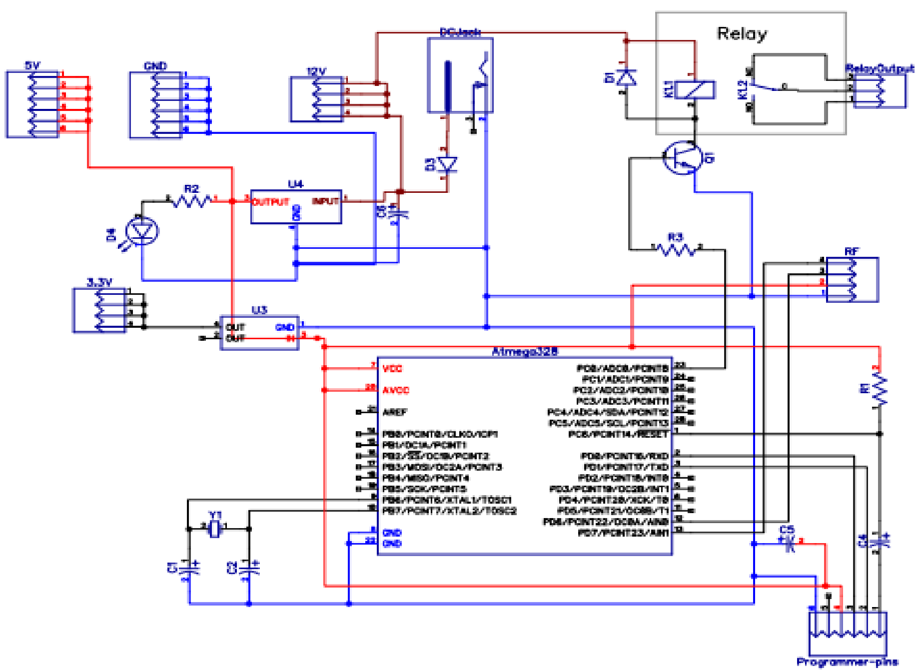



Figure 3.16 Circuit design of SOC section

- The power rail pins of +12V, 5V, and 3.3V are on board to give the supply to sensors and actuators.
- The Vcc, GND, and OUT pins of the relay are connected with +12V, GND, and pin-23 via 10kΩ resistance of the customized atmega328 board.
- The Zigbee is connected to pin-12, 13 of the customized atmega328 board and Vcc and GND are connected to +3.3v and GND.
- Onboard +12V to +5V convertor is connected to +Vcc and GND pins of the atmega328 microcontroller.

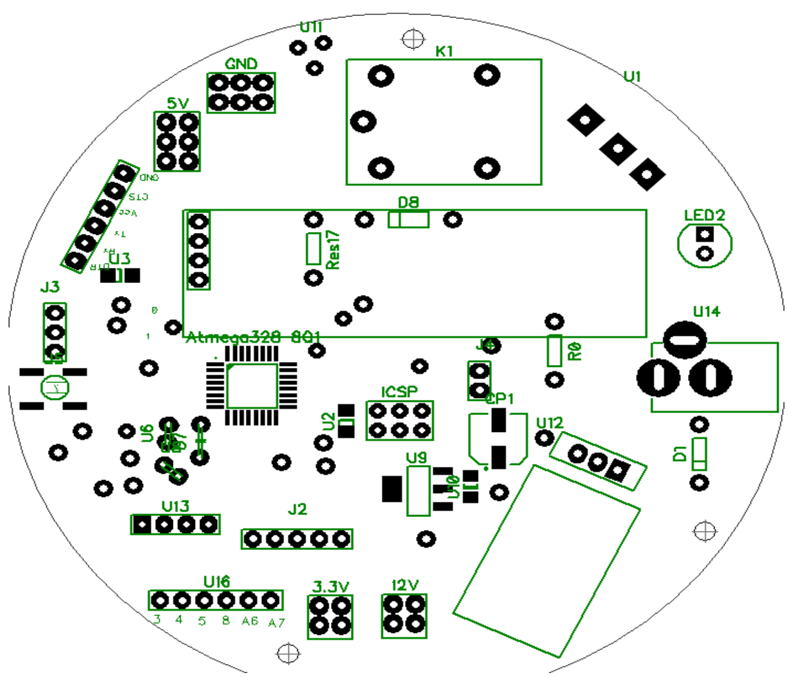



Figure 3.17 PCB layout of SOC device

The HE JQC3FC relay is connected to the atmega328p microcontroller, which regulates the hooter, as shown in Figure 3.18. The 2.4GHz RF module receiver was used to receive data from the monitoring and detecting sections. The sensor array has a number of digital and analog pins. The output voltage is regulated to 12 volts by the LM7812 regulator, which is incorporated on the board. The input voltage can be adjusted to +5v or +3.3v for interfacing IoT sensors. The +Vcc and GND pins of the atmega328 microcontroller are connected to the onboard +12V to +5V converter.

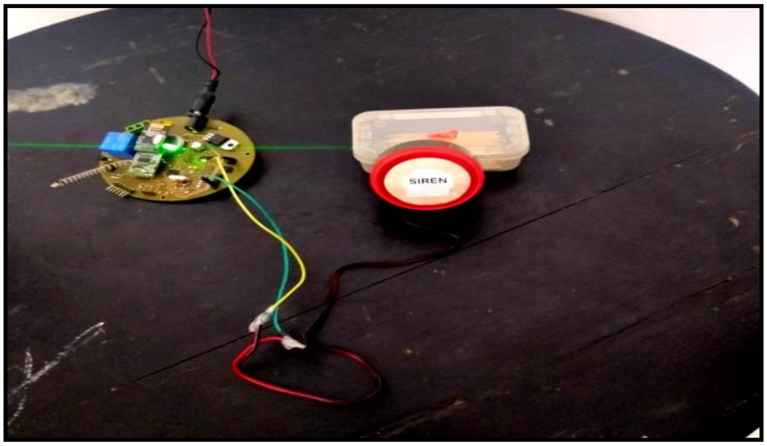



Figure 3.18 Hardware prototype of SOC device

### 3.1.4 Gateway

The data from the sensor nodes is received by the gateway, which then communicates with the IoT cloud server over the internet. The gateway includes a LoRa and Wi-Fi module for communication between sensor nodes and the cloud server. The data received from the monitoring section via LoRa communication protocol is displayed on the LCD. Furthermore received data is communicated to the IoT cloud via a Wi-Fi module that interfaced with a microcontroller. Figure 3.19 gives the block diagram of the gateway.

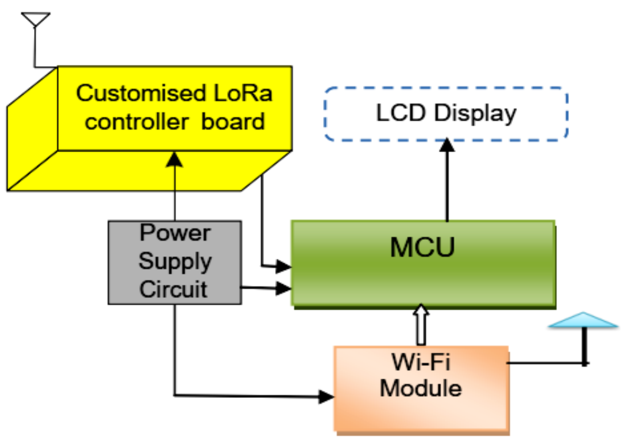



Figure 3.19 Gateway

The gateway is simulated in a proteus simulation environment as shown in figure 3.20. Here temperature sensor and NMCU are interfaced with a microcontroller. The triggered sensor data is displayed in LCD. Moreover, data is communicated through Node MCU and displayed in a virtual terminal.

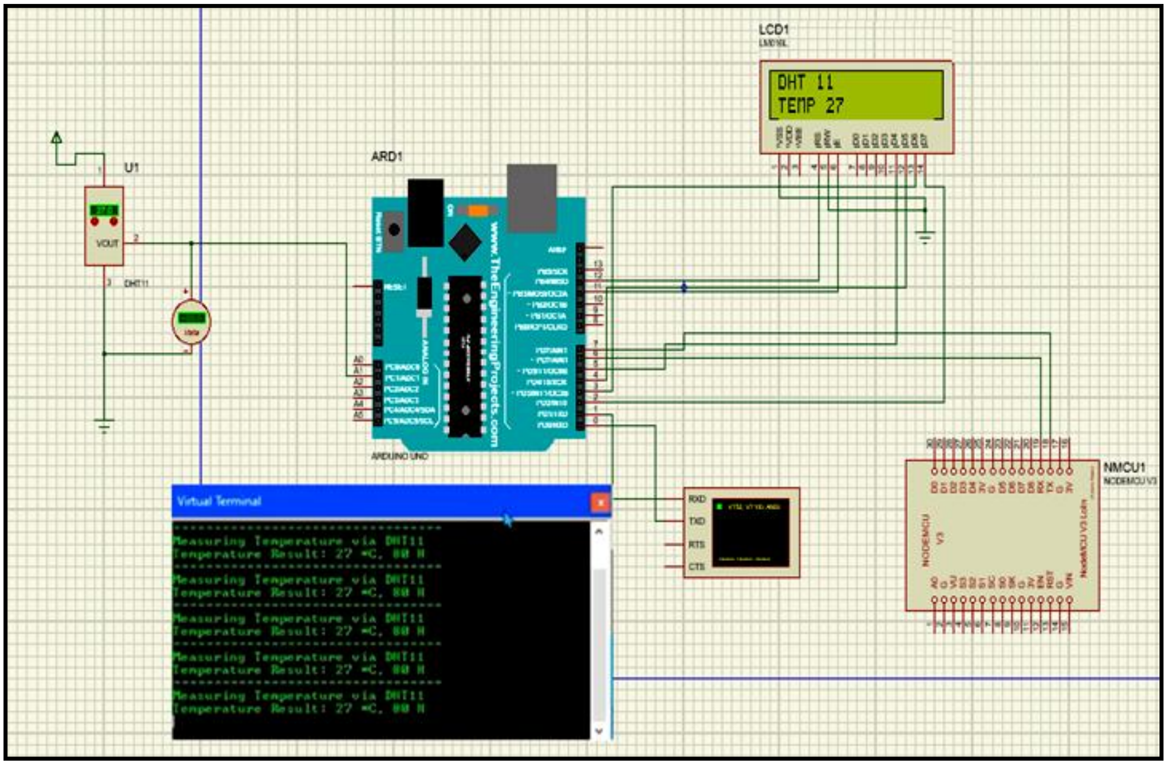



Figure 3.20 Gateway Simulations with Node MCU

The circuit design and PCB design of the gateway is shown in the figure. 3.21 and 3.22. The ATMEGA328 is an 8-bit microcontroller. The controller's operating voltage is between 1.8 and 5 volts. The SX1278 LoRa module is a transceiver radio frequency (RF) module developed by SEMTECH. The frequency range of this module is 137MHz to 525MHz. LoRa highest data transfer rate is 300kbps. The sensor node power source is made up of a bridge rectifier and an AC step-down transformer. The voltage regulators LM7812 and LM7805 are included in the sensor node to handle the various power supply of 12 V and 5V. Hardware module for IoT cloud devices based on the ESP8266 12e series. This device has 9 digital pins, 1 analog pin, 128kBytes of memory, and 4MB of storage space.

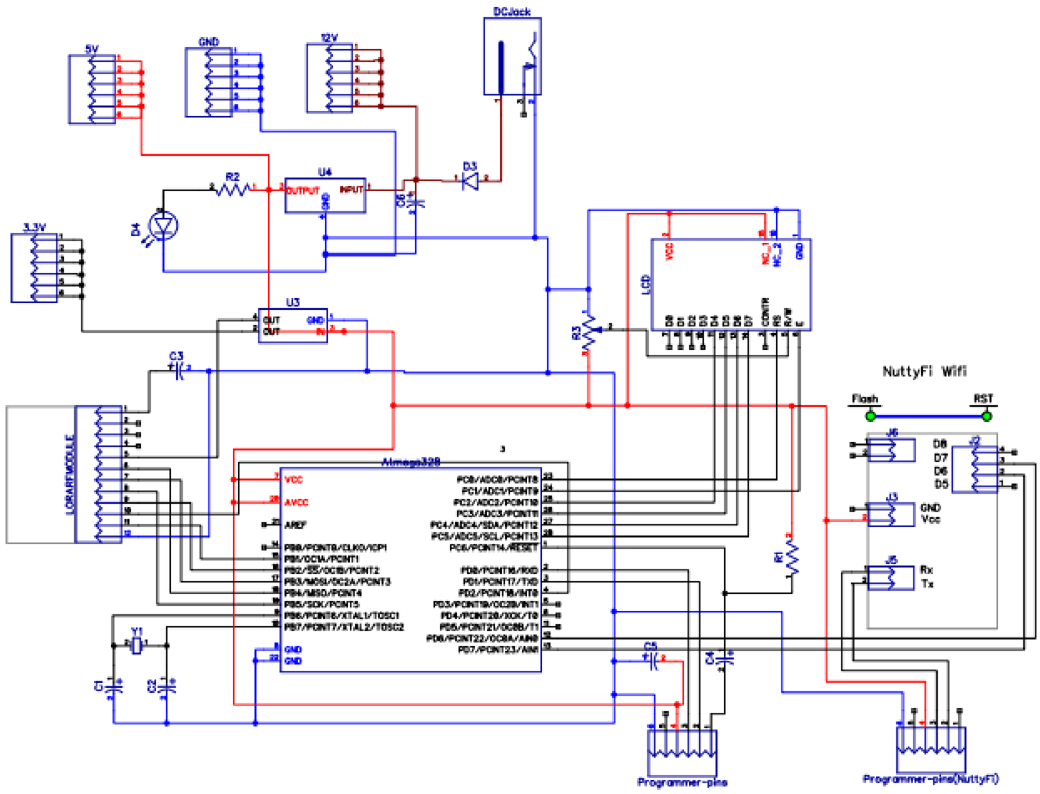



Figure 3.21 Circuit design of Gateway

- The pins-1 and 2of LCD are connected VCC and GND of the customized atmega328 board.
- The 10K POT variable pin is connected with pin-1 of the customized atmega328 board to control the contrast of the LCD.
- The pins-D4, D5, D6, and D7 of LCD are connected with 25, 26, 27, and 28 pins of customized atmega328 board.
- The MOSI, MISO, SCK, GND, Vcc and RESET pins of the LoRA modem are connected with 17,18,19, GND, +5V and RESET pins of customized Atmega328 board.

- The Pin 12, 13 GND, and Vcc of customized atmega328 board are connected with TX, RX, GND, and +5V pins of ESP8266 Wi-Fi modem.

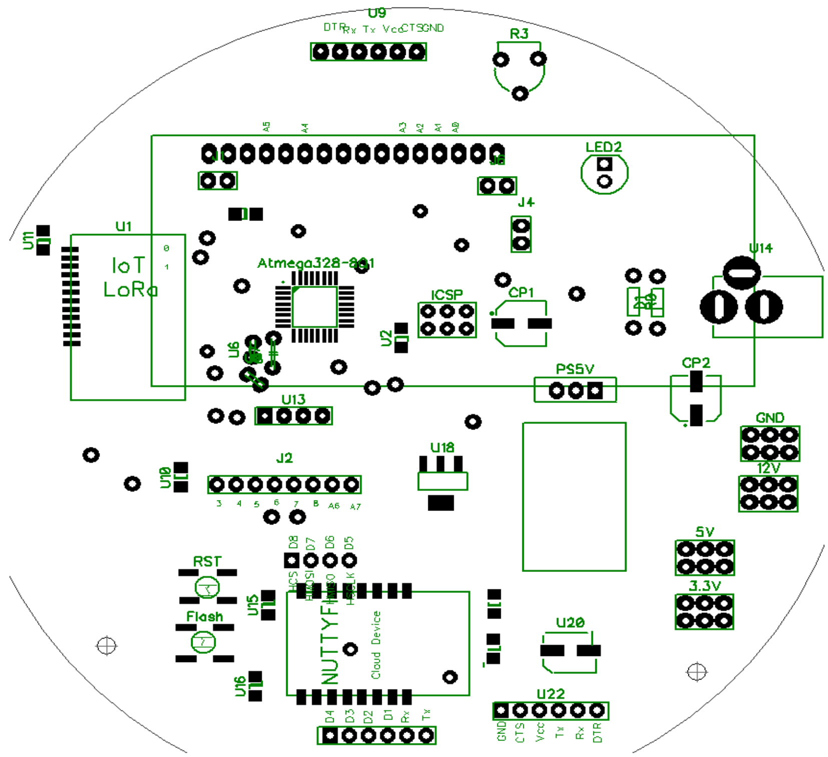



Figure 3.22 PCB Layout of Gateway

The LoRa modem acts as a receiver in the gateway, assisting the gateway in receiving data from the sensor node. A cloud device is a hardware device based on ESP8266 12e family. The advantages of using a cloud device are as follows: Support for Wi-Fi networks is integrated, the board is smaller, and it is less expensive. The LM7812 regulator is built within the gateway and regulates the output voltage to 12 volts as shown in figure.3.23. The gateway is important in receiving information from various sensor nodes via the LoRa module to communicate between the sensor node and the end-user. The data obtained through LoRa communication from the monitoring section and drone yard is displayed in the LCD.

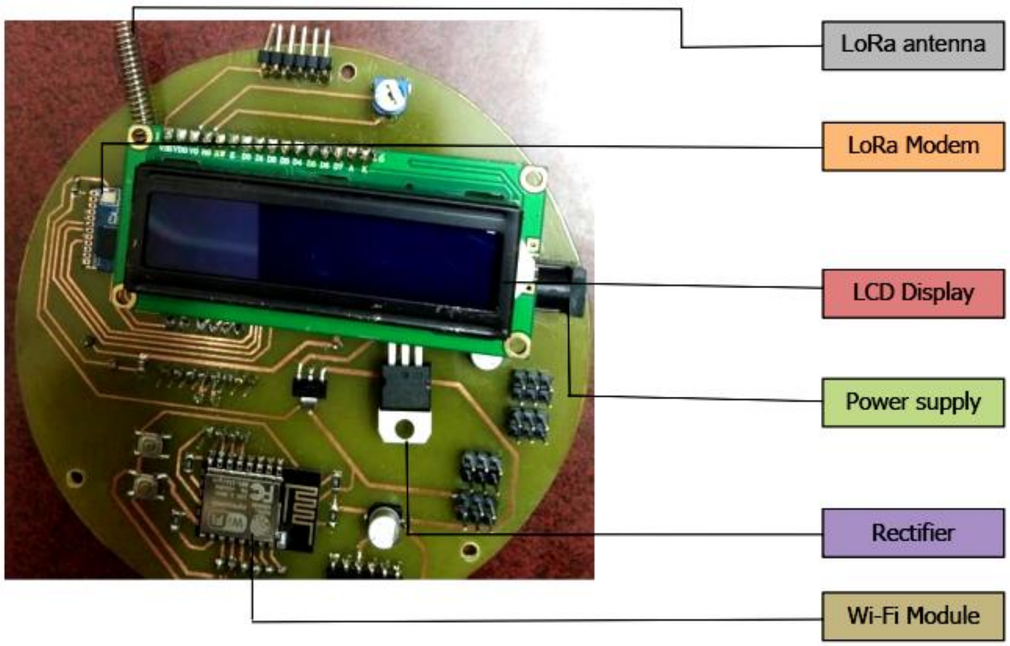



Figure 3.23Customized hardware prototype of Gateway

Furthermore, data is sent to the IoT cloud via the ESP8266 Wi-Fi device, which is embedded to the microcontroller.Figure.3.24 shows the methodology of gateway using a flowchart.

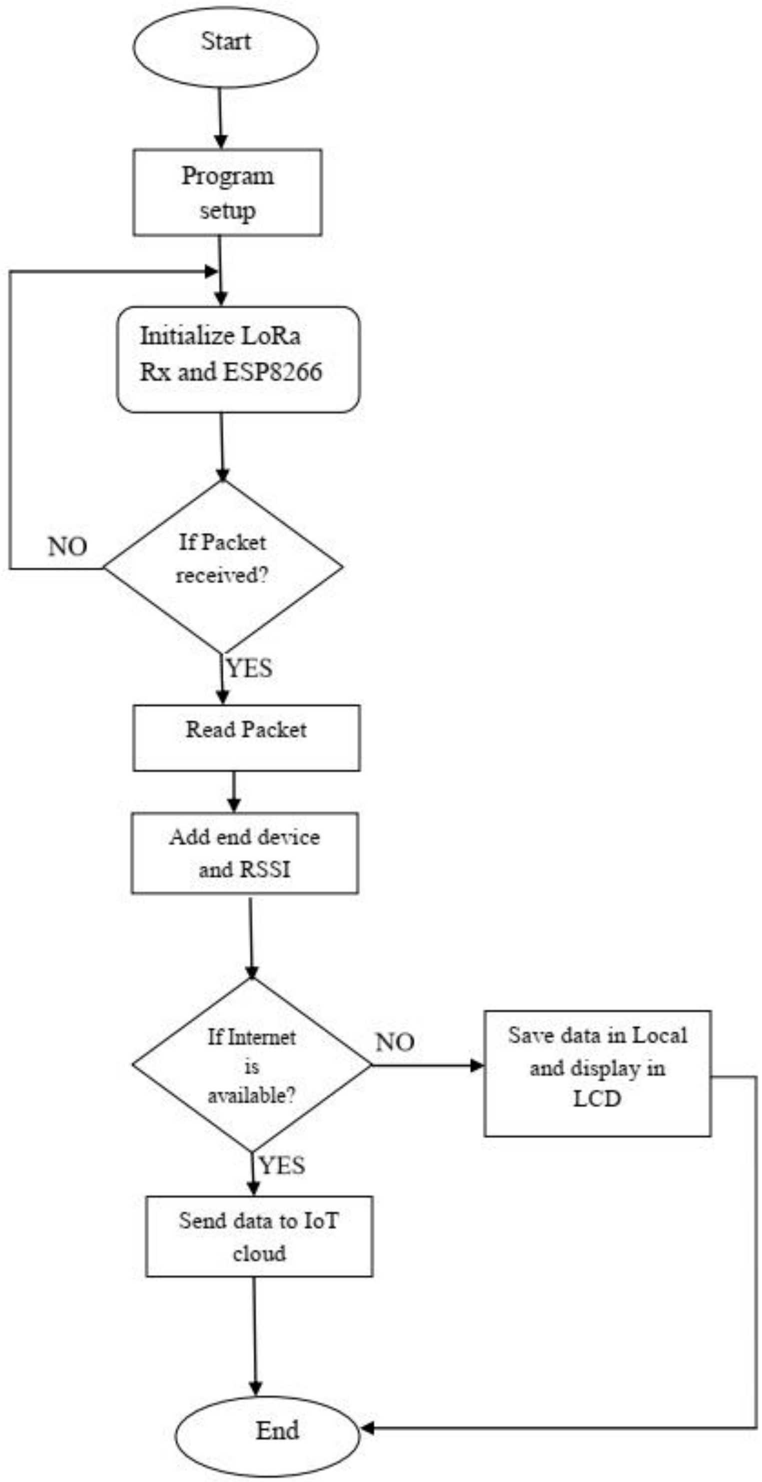



Figure 3.24 Methodology of Gateway

### 3.2 Sensor Components

**a) Temperature sensor:** Pre heating of Oil before while transportation through the pipeline is highly essential to reduce the viscosity of the fluid. For smooth pumping temperature of the oil is maintained between $30^0$ C to $40^0$ C. Figure 3.25 shows the DS18B20 temperature sensor with sensing range -55°C to 125°C and voltage consumption of max 5V.

Figure 3.25Temperature sensor

**b) Humidity Sensor:**

The humidity sensor is useful in pipeline monitoring to check the moisture level in the pipeline before transporting oil. The moisture level is to be less than 25% before the transportation of oil through the pipeline. Figure 3.26 shows the DHT11 humidity sensor. Power supply 3.5V to 5.5V, Humidity range: 20-80% RH

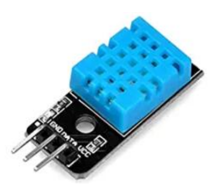


Figure 3.26 Humidity sensor DHT11

**c) Pressure sensor**

This sensor is used to measure the pressure variations of the pipeline.Figure.3.27 shows the Moligh doll pressure transducer. The sensing range up to 1.8 Mpa. Working voltage 5V DC.

Figure 3.27 Pressure sensor

- **Flow Rate Sensor:** The sensor is used to measure flow rate of the oil. This sensor range a flow rate of 1-12 L/Min. the output is generated in terms of pulses. Pulse frequency (Hz) / 7.5 = flow rate in L/min. By using above formula obtained pulses are converted to Lit/Min. Operating Voltage is 4.5V to 18V DC. Figure.3.28 shows the YF-DN 50 flow rate sensor.

Figure 3.28 Flow rate sensor

- **Vibration sensor:** The usage of this sensor is mainly focused to detect third-party damages to the pipeline. Vibration sensors detect vibration using piezoelectric accelerometers. They're utilized to quantify varying accelerations or speeds, as well as regular vibrations Figure.3.29 shows the SW-420 vibration sensor with working voltage of 3.3V.Sensing range of 50 Hz -250Hz

Figure 3.29 Vibration sensor

- **Acoustic Sensor:** Acoustic sensors are used to monitor the sounds of leaks of the pipeline. It detects the intensity of sound where sound is detected via a microphone.. Figure.3.30shows the LM 393 acoustic sensor. Operating current 4-5 mA and induction range 3 KHz to 6 KHz.

Figure 3.30Sound sensor

- **Smoke detection sensor:** Smoke sensors are utilized to distinguish smoke when pipeline harmed and spills oil it bursts into flames.Figure.3.31 shows the MQ-4 smoke sensor. Detection Concentration: 500-10000ppm, Sensitivity to methane, Operating Voltage: 4.5V to 5V DC.

Figure 3.31 Smoke detection sensors

### 3.3 Chapter Summary

The chapter presents system architecture for monitoring the oil pipeline. The sub-modules of the architecture Sensor nodes, SOC, LoRa gateway are illustrated with block diagrams, PCB design, circuit, proteus simulations, and customized hardware boards and their importance of each component and their interfacing. Furthermore, various IoT sensors used to monitor pipeline monitoring are addresses with their specifications.

# CHAPTER-4

# NETWORK PERFORMANCE ANALYSIS

The construction of the LoRa network and Zigbee between sensor nodes and gateway are discussed in this chapter. The calibration of certain LoRa field parameters like spreading factor (SF),Bandwidth, Code rate, link budget, and receiver sensitivity is performed during the establishment of an interlink using LoRa sensor node and gateway in the OPNET simulator and set the network parameters for the real-time deployment of the network. OPNET simulator is also used to examine various Zigbee network parameters such as throughput, retransmission rate, and packet error rate and data traffic. The power consumption of solar-powered sensor nodes and sensors is assessed.

### 4.1 OPNET Simulator

The OPNET Simulator is used to replicate the behavior and effectiveness of any network. OPNET Network Simulator stands out from other simulators because of its strength and adaptability. It enables you to design and simulate various network topologies. OPNET Network Simulator is a free and open-source program. This Simulator provides information on a large variety of project situations. It is a special simulator to design and analyze the various long and short-range communication protocols. It creates a virtual platform for simulating, evaluating, and forecasting network performance. Project creation environment of OPNET simulator is shown in figure 4.1. It provides a larger set of features aimed at improving research and development in networking. Design and test wireless communicating protocols, as well as assess improvements to standards-based protocols. Simulate all network kinds and technologies, including IoT, LTE, and WLAN, to compare and contrast the effects of various technological designs on end-to-end behavior. It allows you to speed up R&D initiatives and save money by testing and showcasing technological concepts before they go into production.

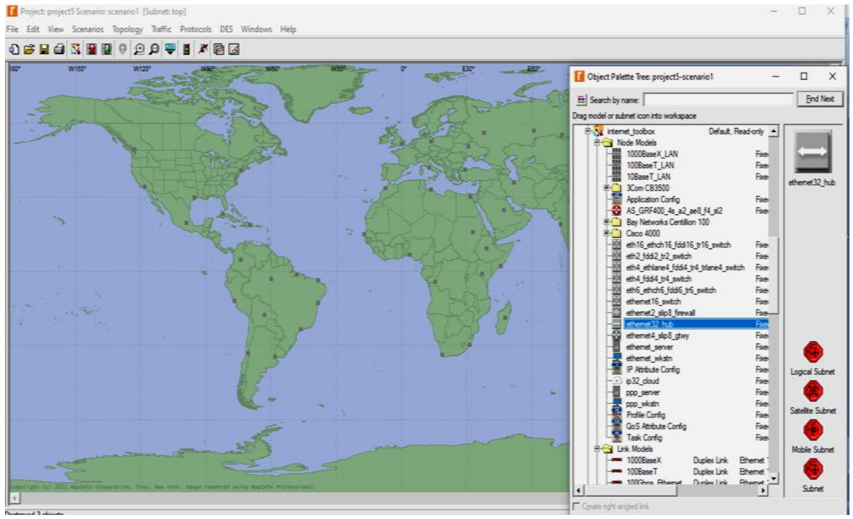


Figure 4.1 OPNET simulator

### 4.2Framework for LoRa Network

Long Range (LoRa) is a wireless communication technology that combines low power consumption with a long range and an unlicensed frequency. While range varies greatly depending on the region and potential obstacles, LoRa normally has a range of 10- 15 km. The simulation of the LoRa sensor node and Gateway using the OPNET simulator is discussed.

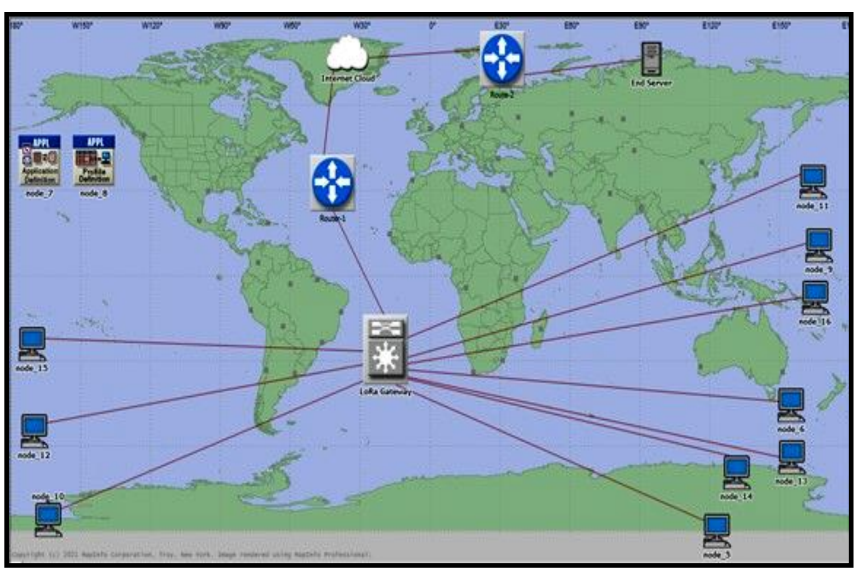



Figure 4.2 Framework of LoRa in OPNET

The LoRa communication protocol has a lot of significant characteristics that are used to assess the network's performance. Figure 4.2 shows the simulation of LoRa network with 10 fixed sensor nodes, gateway and IoT cloud which establish network connection. The following is a study of SNR, RSSI, Bit rate, Link budget, and LoRa sensitivity. The parameters considered are shown in table.4.1.

Table 4.1 LoRa network parameters

| Parameter | Value |
|---|---|
| Spreading Factor | SF7 to SF12 |
| Channel bandwidth | 125KHz ,250KHz, |
| Code Rate | 4/5 |
| Channel Payload | 433 MHz ,On |
| Start and Stop Time | Infinity |
| Payload | 35 bytes |

The received signal strength indicator is used to determine the signal's strength that how best a receiver can receive a signal from the sender. Its signal power is measured in dBm. Signal strength is strong if RSSI is -30dBm and poor signal strength with -120dBm which is minimum. Figure. 4.3and Table.4.2 shows the variation of RSSI value with distance. The strength of the signal is decreased with distance. At 200m -45dBm, 2850m -73dBm, and at -75dbm is achieved at 4125m which is indicates good strength of the signal.

Table 4.2 Received signal strength of Lora with distance

| **Bandwidth** | **Distance (m)** | **RSSI (dBm)** |
|---|---|---|
| 500 | 200 | -45 |
| 500 | 800 | -54 |
| 500 | 1600 | -65 |
| 500 | 2850 | -73 |
| 500 | 3299 | -79 |
| 500 | 4125 | -75 |

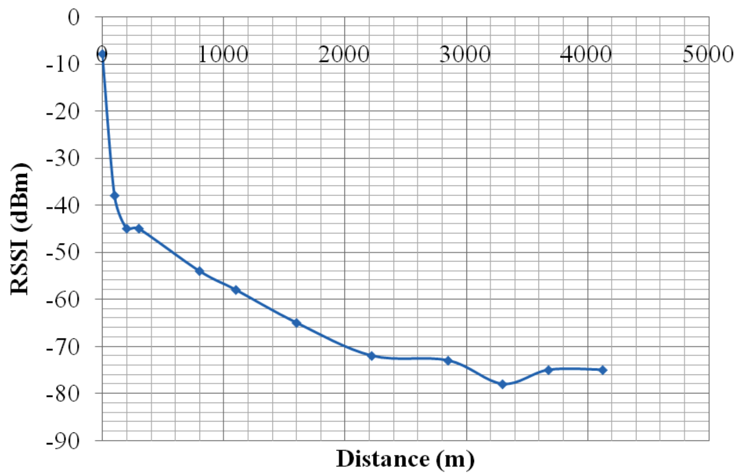



Figure 4.3 RSSI Vs Distance

When a sender sends a signal, the receiver waits a specific amount of time to receive it. This period is referred to as "Time on Air" (ToA).Figure 4.4 demonstrates how TOA varies depending on payload size and spreading variables (SF). The SF-12 has a high TOA of 400 ms with 35 bytes of payload, whereas the SF-7 has a lower TOA of 35 bytes with 20ms. This shows TOA for SF-7 is low with 35bytes of payload which is to be considered.Table.4.3 gives the TOA at payload of 35bytes with various spreading factors.

Table 4.3 Time on Air with various SF

| **Spreading Factor (SF)** | **Payload (Bytes)** | **Band width (KHz)** | **TOA (ms)** |
|---|---|---|---|
| 7 | 35 | 500 | 20 |
| 8 | 35 | 500 | 42 |
| 9 | 35 | 500 | 50 |
| 10 | 35 | 500 | 98 |
| 11 | 35 | 500 | 222 |
| 12 | 35 | 500 | 402 |

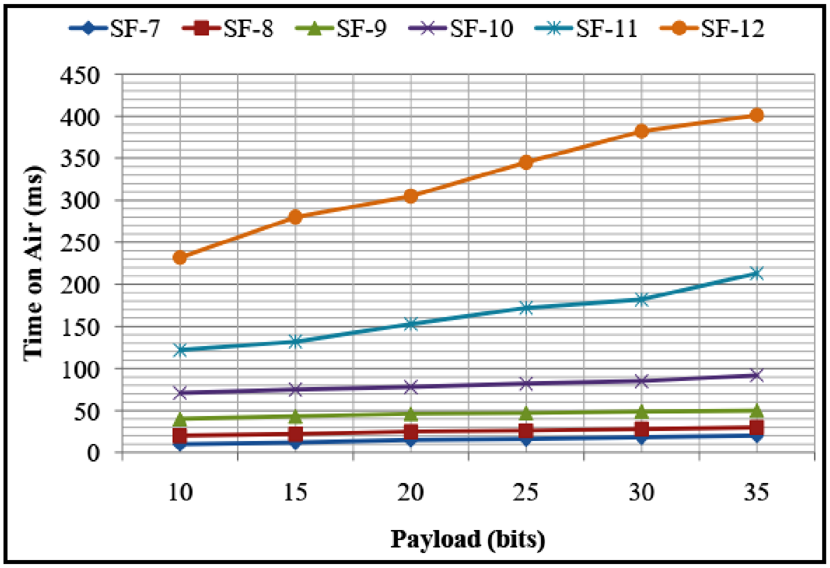



Figure 4.4 TOA vs. payload at different SF

The signal-to-noise ratio is the ratio of transmitted signal powers to the undesired signal. The SNR should keep as low as feasible in order to ensure that demodulation at the receiver end is simple and the signal is accurately decoded.

Table 4.4Signal to noise ratio with distance

| Bandwidth(BW) | Distance (m) | SNR (dB) |
|---|---|---|
| 500 | 50 | 32 |
| 500 | 100 | 30 |
| 500 | 200 | 28 |
| 500 | 400 | 28 |
| 500 | 600 | 25 |
| 500 | 1000 | 24 |
| 500 | 2200 | 19 |

It employs forward error correction (FEC) methods and the spreading factor to increase LoRa performance, resulting in substantial SNR gains. The SNR range is between 20 and +10 dB in particular. Table.4.4 shows the increasing distance, the signal-to-noise ratio (SNR) is seen to drop. It has a good signal power up to 2200mts with 19dB as shown in figure.4.5.

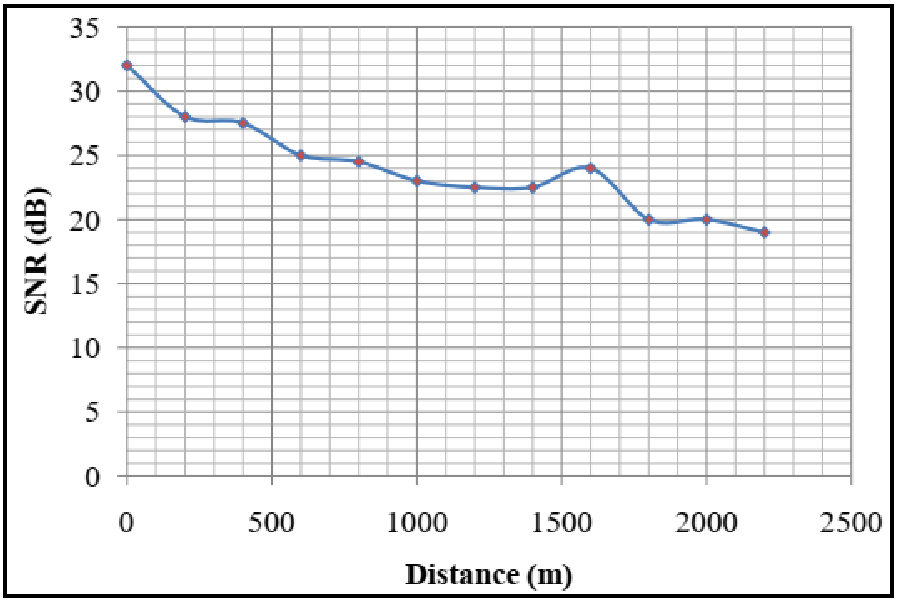



Figure 4.5SNR Vs Distance

The packet error rate (PER) is used to evaluate the receiver performance of an access terminal. The number of error packets is divided by the total number of received packets. Simulation results in figure 4.6and Table 4.5demonstrate the packet error rate (PER) for various payload sizes. PER with a payload size of 20 bytes has been observed to be about 7% and 25% for spreading factor SF-7 and SF-12, respectively. Spreading factor SF-7 and SF-12 have a PER of nearly 5% and 45 %, respectively, with a payload size of 35 bytes. From the above results, it is observed that SF-7 gives less Packet error rate at 20 bytes and 35 bytes of payload.

Table 4.5 Packet error rate with various SF

| **Spreading Factor (SF)** | **Payload (Bytes)** | **PER (%)** |
|---|---|---|
| 7 | 35 | 4.5% |
| 8 | 35 | 5% |
| 9 | 35 | 5.5% |
| 10 | 35 | 17% |
| 11 | 35 | 34% |
| 12 | 35 | 43% |

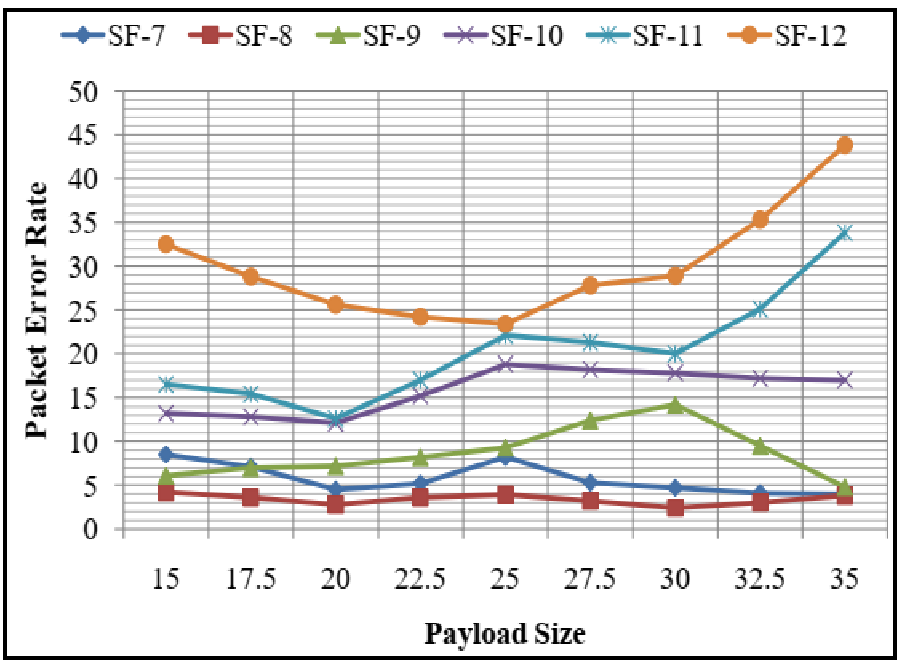



Figure 4.6 PER Vs Payload size

The data rate is number of bits transferred between the transmitter and receiver during transmission. Spreading factor, code rate and bandwidth are the parameters considered to calculate bit rate. The bit rate of Lora for various spreading factors is shown in Figure 4.7. BW8-125 KHz, BW9-50 KHz, and BW10-500 KHz are considered to study bit rate. The bit rate gradually increases at the BW 10 and CR1 in every SF, as can be seen. The LoRa bit rate reached 22k bits per second in SF 7, however it is restricted to 2k bits per second in SF 12. When SF is increased, the amount of data sent during transmission is reduced; therefore SF 7 is the best to consider when transmitting a large amount of data. In table.4.6,Bit rate is observed at bandwidth of 500 KHz and code rate-4/5 with various SF7-SF12.

Table 4.6 Bit rate with various SF at 4/5 code rate

| **Bandwidth (BW)** | **Bit rate (bps)** | **Spreading Factor (SF)** | **Code rate (CR1)** |
|---|---|---|---|
| 500 | 22000 | 7 | 4/5 |
| 500 | 13000 | 8 | 4/5 |
| 500 | 7100 | 9 | 4/5 |
| 500 | 3900 | 10 | 4/5 |
| 500 | 2200 | 11 | 4/5 |
| 500 | 1600 | 12 | 4/5 |

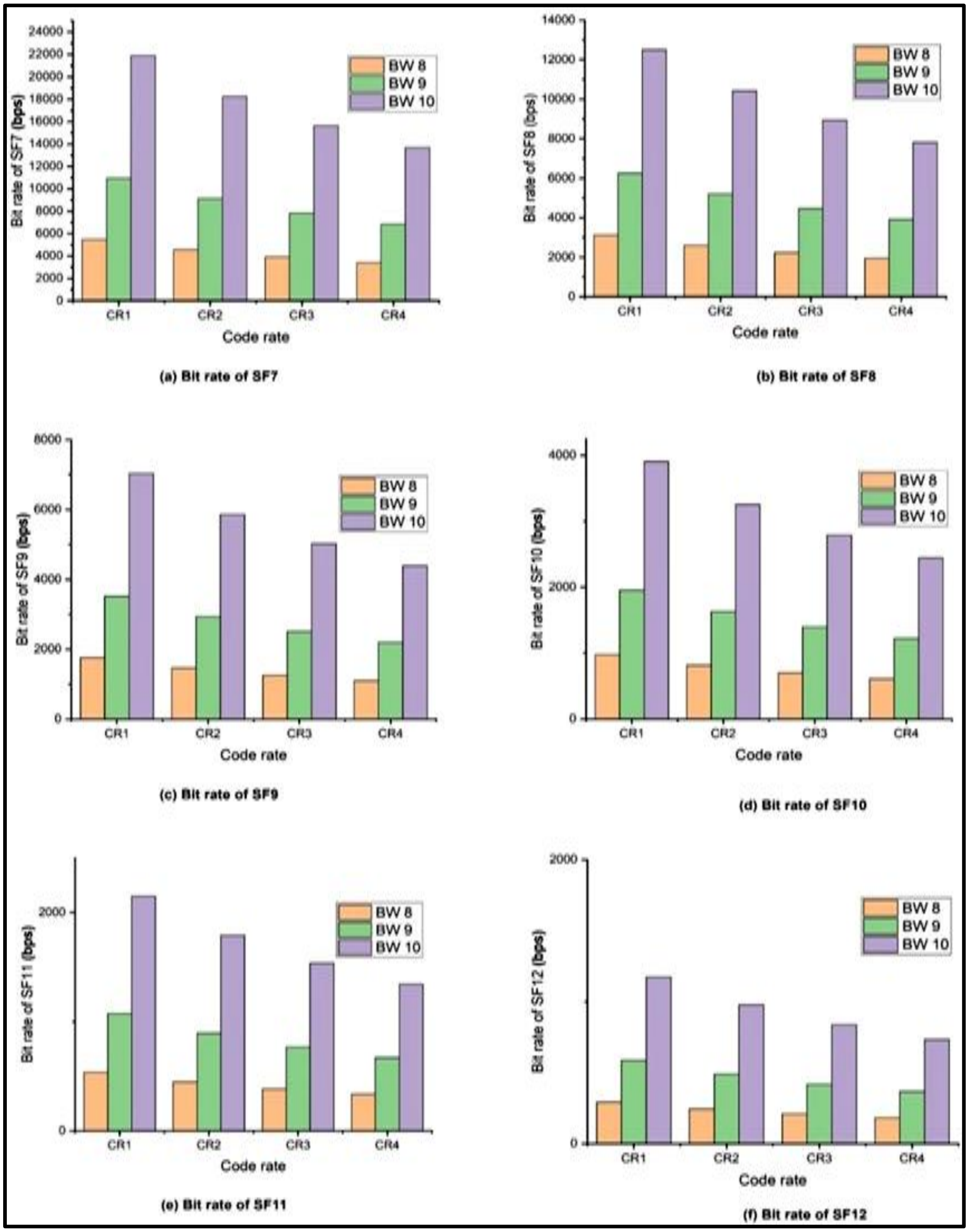



Figure 4.7 Bit rate of SF7-SF12

The receiver's sensitivity is defined as its capacity to amplify weak signals received by the receiver. The input parameters for determining the receiver's LoRa sensitivity are the BW, SF, and noise values. Various bandwidths BW1-125 KHz, BW2-250 KHz, and

BW3-500 KHz are considered to evaluate LoRa sensitivity with uplink communication. Any value for power sensitivity is normally expressed as a negative number, such as 127 dBm, if it is greater than that indicates that it is declining. Figure 4.8 shows the LoRa sensitivity. At BW3, the SF 7 has the highest sensitivity, and at BW 1, the SF12 has the lowest sensitivity. Table 4.7 shows the node sensitivity variations with various Spreading factors with uplink communication.

Table 4.7 Receiver sensitivity at various spreading factors

| **Mode** | **Spreading Factor (SF)** | **Bandwidth (BW)** | **Node Sensitivity (dBm)** |
|---|---|---|---|
| Uplink | SF-7 | 500 | 132 |
| Uplink | SF-8 | 500 | 137 |
| Uplink | SF-9 | 500 | 143 |
| Uplink | SF-10 | 500 | 148 |
| Uplink | SF-11 | 500 | 152 |
| Uplink | SF-12 | 500 | 156 |

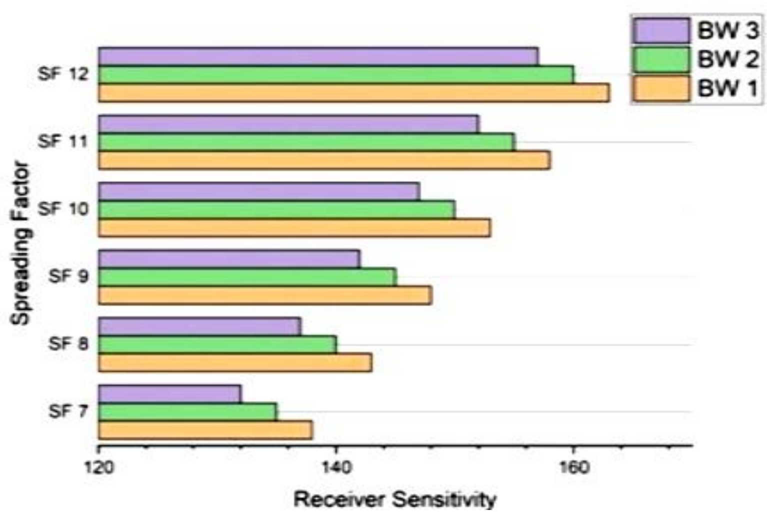



Figure 4.8 Receiver Sensitivity

A link budget is the total of all gains and losses in a system from the transmitter to the receiver via the medium. It is a method of calculating the link's performance. The figure 4.9gives the Link budget with BW 125 KHz, 250 KHz and 500 KHz with antenna power varying from 2dB to 14dB at SF7 and SF12. The link budget increases with every rise in the SF. At 14 dBm, the link budget reached its maximum dBm for SF 12 at 125 kHz. The link budget found a low dBm of 2 dBm for 500 kHz at SF7. From the table 4.8 it was observed that at 500 KHz bandwidth and power 14dB highest link budget 134 dBm is achieved.

Table 4.8 LoRa trades with Link budget with Antenna power at SF-7

| **Mode** | **Antenna TX Power (dB)** | **Bandwidth (BW)** | **Link budget** |
|---|---|---|---|
| Uplink | 2 | 500 | 127 |
| Uplink | 5 | 500 | 124 |
| Uplink | 8 | 500 | 128 |
| Uplink | 11 | 500 | 130 |
| Uplink | 14 | 500 | 134 |

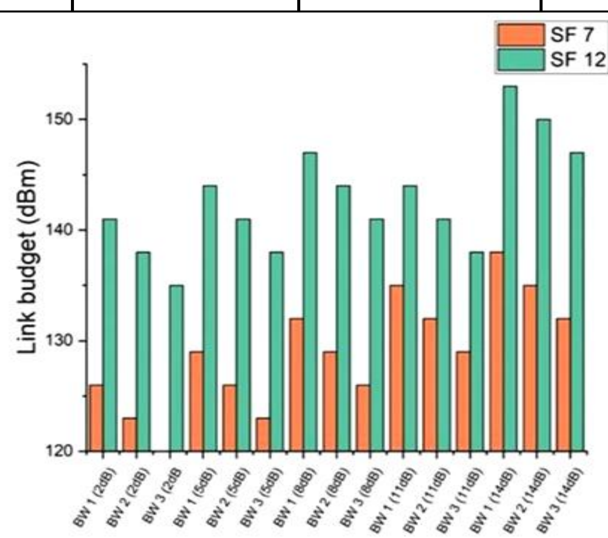



Figure 4.9 Lora Link budget

The following conclusions can be drawn from the above results. All the parameter in simulation is varied with distance of 10Km of range. It was noticed that as the bit rate declines from SF 7 to SF 12, the rise in the SF7 is significantly affected by the bit rate. SF 7 is the spreading factor that needs to be considered for sending a large amount of data at the 500kHz band because the bit rate is high about 22kbps. The PER is less than 7% at payload 35 bytes with SF 7. The link budget is observed at 14db Tx power, SF 7, and 500kHz as suitable specifications for producing the maximum link budget of 134dBm.At 500 kHz, the SF 7 has the highest sensitivity power which is to be considered. The SNR at 2200 m is close to 19dB and signal strength RSSI achieved -75dB at 4Km of range.

As gateway shown in figure 4.10 is capable of receiving sensor data through LoRa communication and interact with the cloud server. This gateway is located in an area where internet access is reliable. As you can see, the data from the sensor node, such as flow rate, temperature, pressure RSSI is shown on the LCD of the gateway. The gateway receives data from a sensor node that is positioned at a range of 2 to 2.5 km. During the experimental phase, effective data reception at a range of 1.8 km was achieved with RSSI -62.


Figure 4.10 Gateway receiving data

### 4.3 Framework for Zigbee Network

Zigbee technology is low-cost and low-power and its best properties make it suitable for embedded applications, industrial control, and home automation, among other things. The transmission distances for Zigbee technology typically range from up to 100 meters depending on various conditions. Figure 4.11 shows the functioning paradigm of the Zigbee framework, in which various nodes use routers to send data to the Zigbee coordinator. Using the network layer and physical layer parameters stated in Table 4.9, the simulation was meant to run for a certain period. Here the analysis is done on the frequency band of 2.4 GHz and 916 MHz and generated results.

Table 4.9 Parameter of Zigbee

| Network Layer | |
|---|---|
| Zigbee Coordinator | 1 |
| Packet size | 1024 kbs (cont) |
| Zigbee End device | 12 |
| Packet interval time | Constant (1.0) |
| Zigbee router | 4 |
| Physical Layer | |
| Transmission band | 2.4 GHz, 915 MHz |
| Transmission Power | 0.05W |
| Receiver Sensitivity | -85 |
| Data rate | Auto calculate |

In this approach, network traffic was created using parameters that varied depending on the device to Coordinator connections. Different network performance measures are investigated using simulations of the Zigbee network model. End-to-end latency between layers, packet delivery ratio, retransmission attempts, and channel throughput parameters performance is examined.

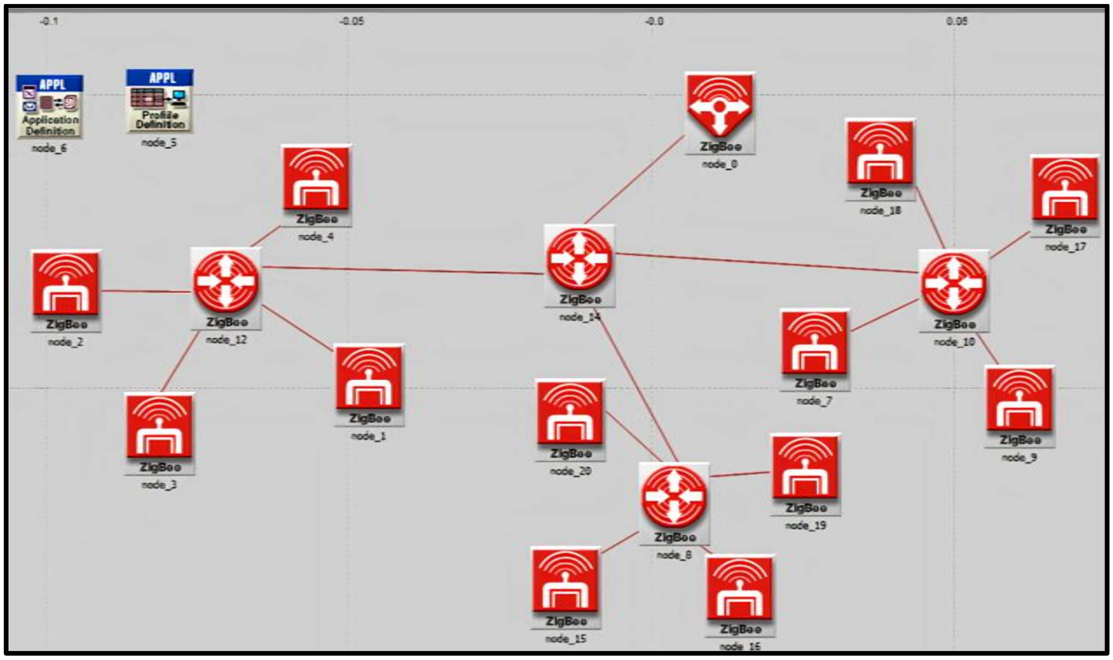



Figure 4.11 Frame work of Zigbee in OPNET

Packet delivery ratio is the parameter where no of packets received by the coordinator to the no of packets broadcasted by the end nodes. As shown in Figure 4.12, each node delivered an average of 3500 bits/sec over the 1600-second simulation period, resulting in a total of roughly 42000 bits/sec sent by all nodes in the network. As shown in figure.5 the coordinator now receives an average of 38000 bits/sec in the data flow. The PDR is close to 0.80. In other words, the Zigbee coordinator receives 90% of correctly received data packets with a 2.4GHz band. The coordinator now gets an average of 16500 bits/sec in the data flow, as shown in Figure 3. The PDR is about 0.91. As a consequence, 91 percent of data packets were sent to the Zigbee coordinator with 916 MHz bands. PDR expression is shown in equation.8.

$$PDR = \frac{DPR}{DPTN1 + DPTN2 + ------ DPTNn} \quad \text{-- (8)}$$

DPR denotes the number of data packets received.

$DPTNn$ is the total number of data packets sent by 'N' nodes.

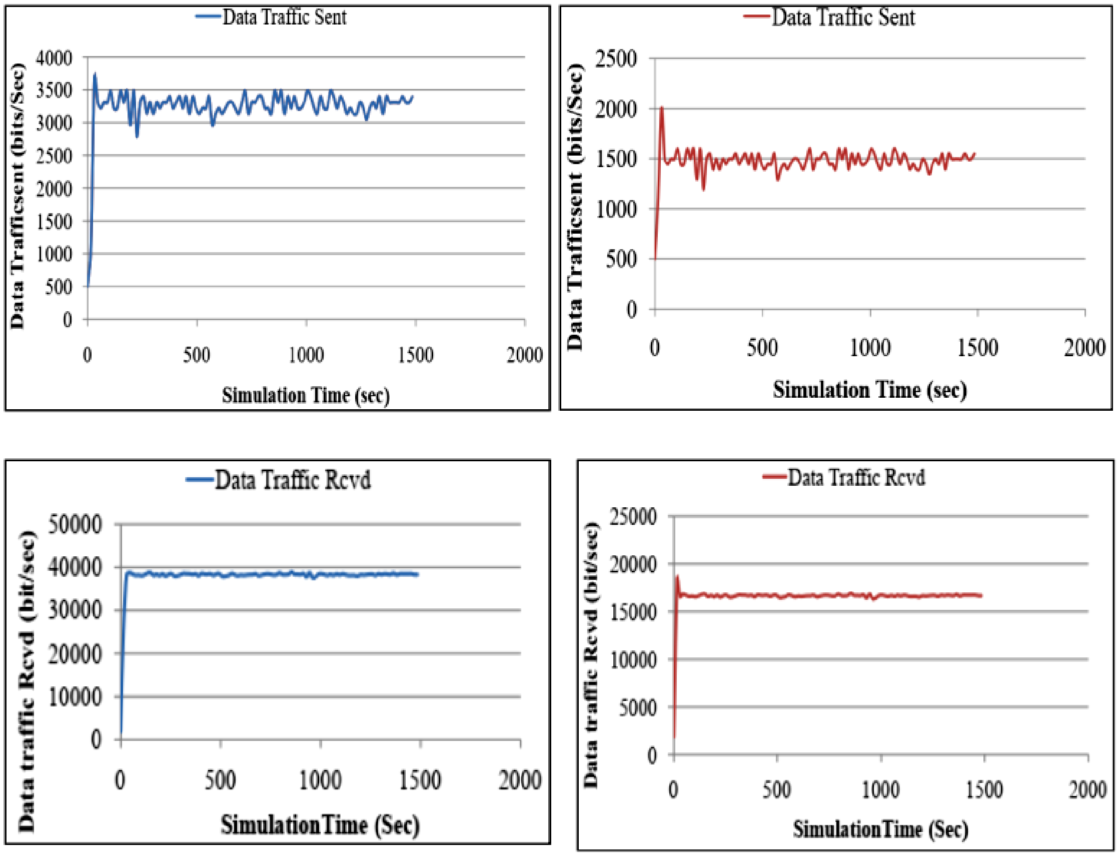



Figure 4.12 Packet error rate for 2.4GHz and 916MHz bands

Retransmission is attempted until a packet is successfully transferred. Figure 4.13 depicts 0.5 packet retransmission attempts during a 1600-second simulated period for both frequency bands.

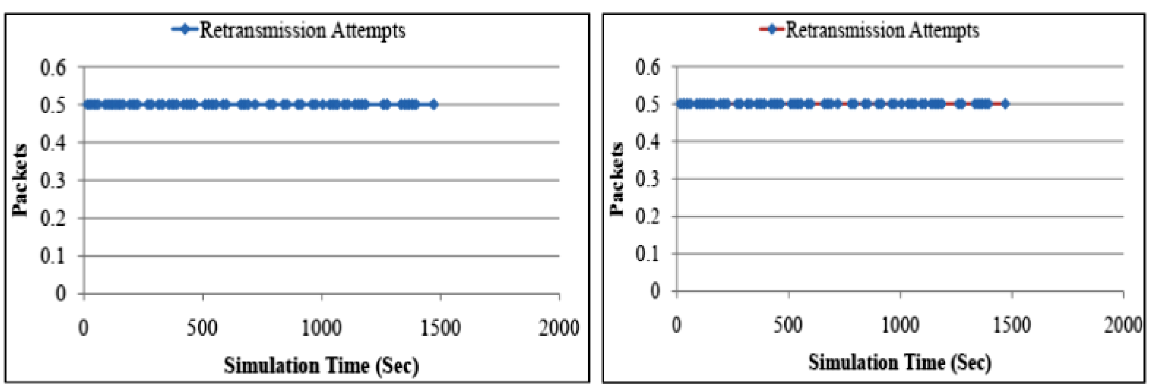



Figure 4.13 Retransmission attempts for 2.4GHz and 916MHz bands

Throughput is the rate at which data is properly transmitted from a source address to a destination address. At the start of the experiment, the greatest throughput was 50kbps, and at 250 seconds, the lowest level throughput was 40kbps. The average carried throughput is 45 kbps for 2.4 GHz and the 916 MHz band the maximum throughput is 28 kbps at the start of the simulation, and at 230 seconds of time frame, the minimal throughput is 15.5 kbps. 18kbps is the average throughput is noticed as shown in Figure 4.14.

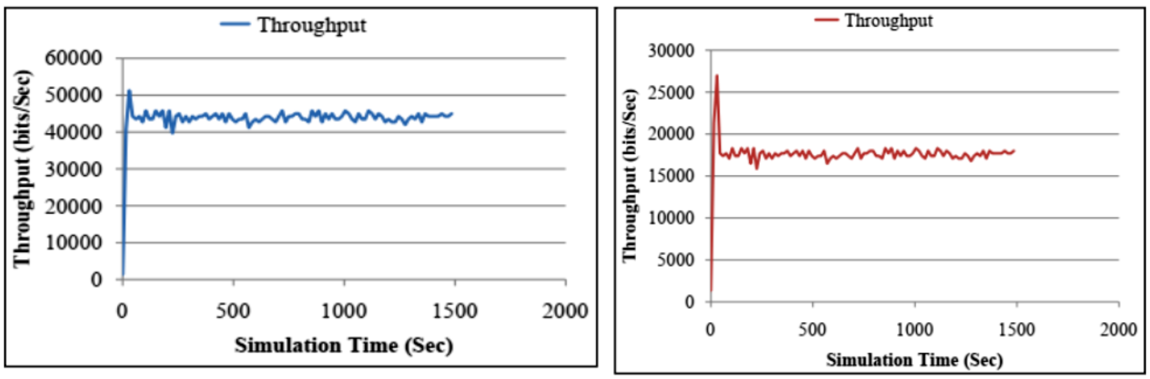



Figure 4.14 Throughput for 2.4GHz and 916MHz bands

The time required packets to travel from their source to their destination in wireless networks is referring to as delay. It consists of the overall time spent on route discovery, queuing, propagation, and transfer. End-to-end latency is depicted in Figure 4.15 at various simulation durations for the 2.4GHz frequency band. At a simulation time of 300 seconds, the greatest delay found is 0.014 seconds, with a minimum of 0.012 seconds at 700 seconds. Finally, the average end-to-end latency is 0.013 seconds is noticed. The maximum delay discovered is 0.18 seconds at a simulation time of 400 seconds, with a minimum of 0.12 seconds at a simulation time of 600 seconds. Finally, the end-to-end latency is 0.15 seconds on average at 916MHz band as presented in figure 4.13. Table 4.10 shows the major outcomes of Zigbee network.

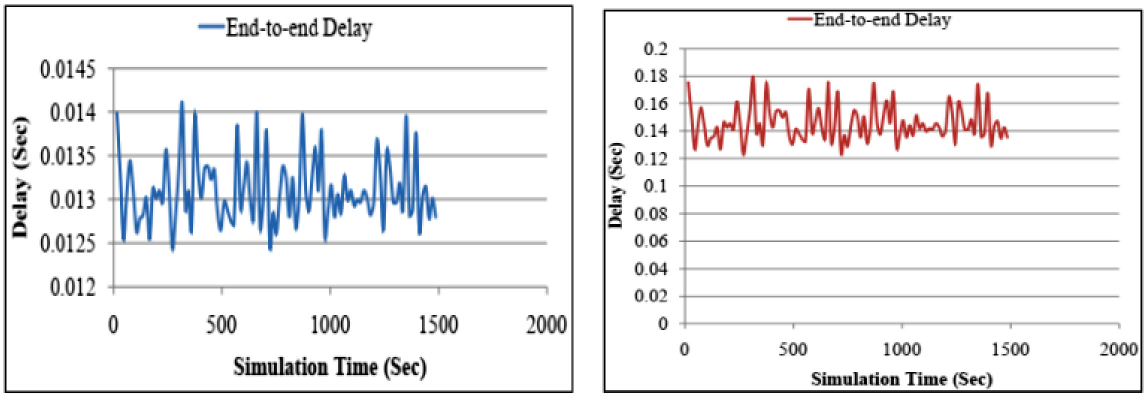



Figure 4.15 End to End delay for 2.4GHz and 916MHz bands

Table 4.10 Results achieved

| Parameter | Averagedata for 2.4 GHz Band | Averagedata for 916 MHz Band |
|---|---|---|
| PacketDeliveryratio | 80% | 91% |
| RetransmissionAttempts(Packets) | 0.5 | 0.35 |
| Throughput(bits/Second) | 45000 | 18000 |
| End to end delay | 0.013 | 0.15 |

### 4.4 Power Analysis

The majority of the time, in pipeline management, the sensor nodes is put in remote places. Furthermore, sensor node battery life is a challenge because battery life depletes owing to varying ambient conditions. As a result, it is the best method for harvesting energy from renewable sources for sensor motes. Energy harvesting is a better system for powering sensor nodes so that they can execute tasks including sensing, preprocessing, and data transport. Cisco packet tracer (CPT) is used to assess the battery life of sensor nodes powered by solar panels. The simulation illustrates the lifetime of the nodes as well as data transfer from end nodes to the hub, hub to a central server, and lastly to IoT sensors and devices. The simulation panel is shown in the illustration. A power meter is used to link each renewable resource to calculate the power usage. In the time column, the timestamp details of the IoT devices are represented. With a time of 0.33 seconds, the IoT 2 device is connected to the network. Within 0.61 seconds, devices IoT0 and IoT1 are connected. The total time it took for the device to connect is listed as 34.6 seconds. A scenario of power 160 Watt along with 136Wh is considered as represented in figure 4.16.

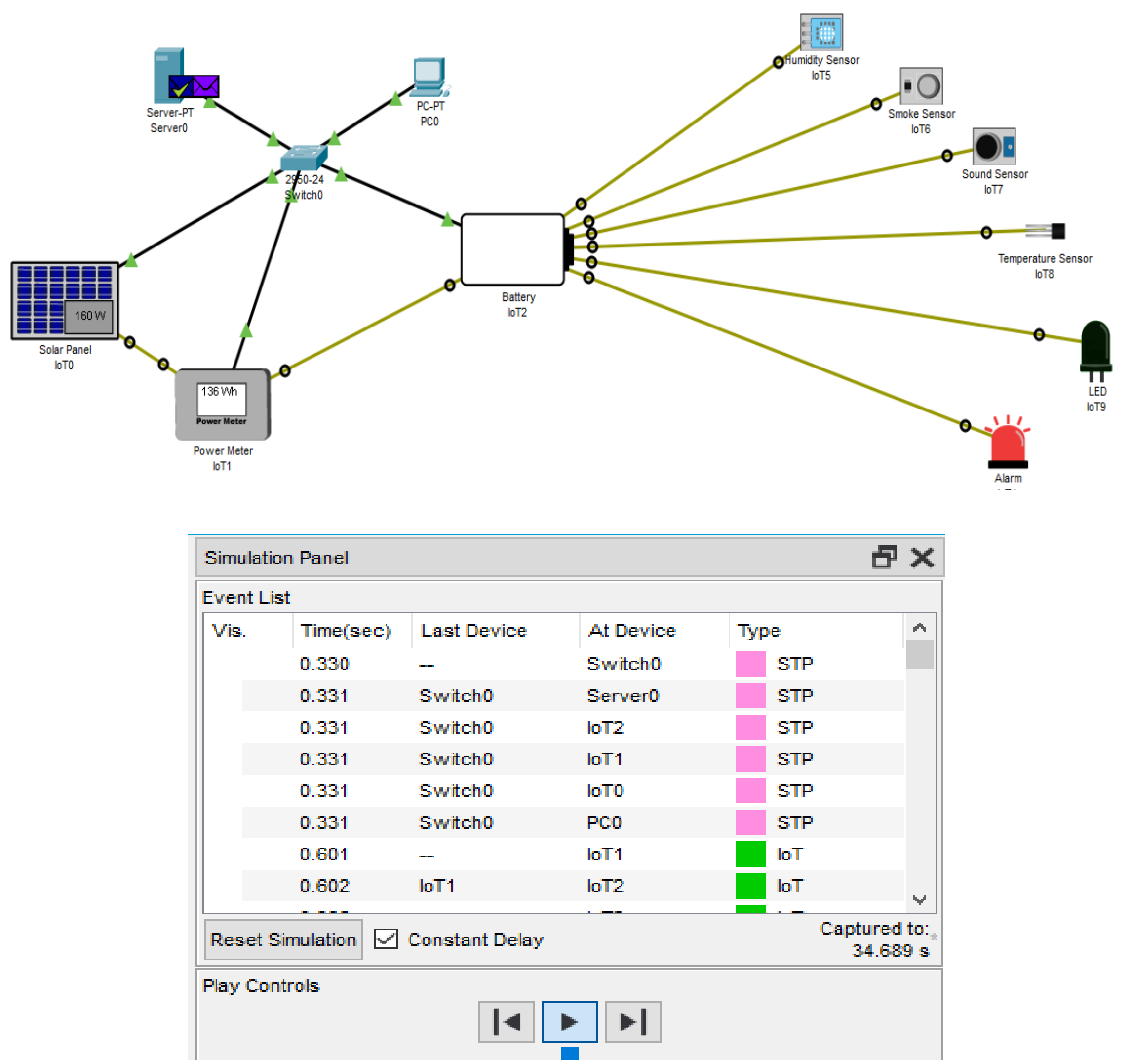



Figure 4.16 Sensor node energy conservation using renewable resource

## 4.5 Chapter Summary

This chapter provides the communication link setup of the LoRa network and Zigbee between sensor nodes and gateway. A simulation is performed during the interlink set up to analyze the network behavior of the LoRa network parameters. The LoRa network parameters SF-7, bandwidth (500 KHz), Code rate (4/5) are set as parameters to test in real time deployment of the system. In addition, throughput, retransmission rate, and data traffic are all Zigbee network characteristics are analyzed with 2.4 GHz and 916MHz bands. An energy harvesting simulation for sensor nodes based on Cisco Packet Tracer to test battery life with solar power.

# CHAPTER-5

# UNMANNED AERIAL VEHICLE

This chapter presents the design of drones for oil pipeline monitoring. Necessity of drones in oil industry is enhanced and the design of quadcopter drone using AutoCAD software is elaborated with simulation results. Moreover, the assembling of drones using IoT components is discussed. Finally, the methodology of drone working is addressed using a flowchart.

## 5.1 Introduction to Unmanned Aerial Vehicles

Oil pipelines are commonly found in difficult to monitor. Damage to such installations, as well as equipment failure, can have a huge environmental impact and result in a loss of revenue, disrupting the oil industry. It is a primary goal to improve the security of oil and gas pipelines. A significant system of legislation and regulation is focused at improving the integrity and reliability of hydrocarbon pipelines. UAV (Unmanned Aerial Vehicle) also called a drone is an unmanned aircraft that can be controlled remotely or fly separately using autonomous systems with pre-programmed plans. Some of the third-party damages and environmental damages and robbing oil cause pipeline damage. If there is a malfunction with the pipeline network's equipment, such as a leak, results in environmental harm, health difficulties, and financial loss.

Monitoring oil pipeline networks necessitates a regular examination of the pipes' physical state and functionality to reduce the danger of spill, and theft of actual accidents with their environmental consequences. Detailed mapping for monitoring entails establishing a baseline state and identifying any changes that occur throughout the pipeline's life events. Spills and leaks must be detected quickly if pipeline damage occurred. Visual inspections have been used to monitor pipeline networks in the past. The majority of the monitoring is still done using traditional methods, mostly by occasional patrols on foot and aerial observation with helicopters [8]. Furthermore, the primary drawback of monitor and inspection systems is the risk of late fault finding, after oil output has been decreased or the environment has been affected.

### 5.2 AutoCAD Design

Drones play an important part in getting the greatest images in a variety of situations. Drones come in a variety of sizes and shapes, and they can be used for a variety of purposes. Drones with fixed wings, single-rotor helicopter drones, and multi-rotor drones are all available. A quadcopter drone, also known as a quad rotor helicopter or quad rotor, is a multi rotor aircraft with four rotors that lift and propel it. The many propellers provide tremendous lift and accurate control to the pilot. Quad copters are categorized as rotorcraft rather than fixed-wing aircraft since they employ a set of rotors to generate lift. To regulate lift and torque, they employ a variety of RPM. The torque load and thrust/lift characteristics of a vehicle can be changed by changing the rotation rate of rotor discs. Figure.5.1 shows the diagrammatic view of the quadcopter.

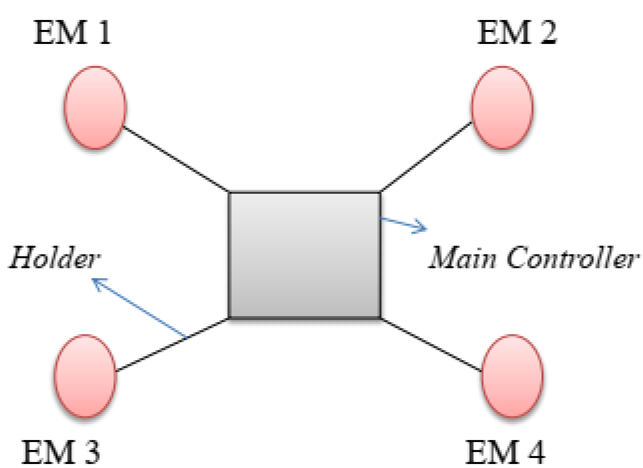



Figure 5.1 Quadcopter structure [161]

Quad rotor for interior flying in densely populated areas with little danger of harming the vehicle, its users, or the environment [161]. In the beginning, the flying behavior was studied in a controlled setting for hovering. Then they created a computer model that could handle greater flight dynamics [162]. The Dragonflies X-Pro was similarly built with four horizontal rotors and no vertical rotors, which set it apart from typical helicopters. The rotational speed of the rotors was the only variable that could be changed while in flight [163]. Beyond the 3D design basic capability, modern Computer-Aided Design (CAD) programs are jam-packed with incredible technical possibilities. For example, Solid works provides sophisticated engineering tools for design, modeling, and analysis, including flow simulation with integrated CFD solvers and motion assessment [164][165]. The iterative method begins with an optimal block mass while setting design parameters, taking into account the hole and obstacle boundaries. The algorithm is created in such a way that bulk is removed in a streamlined manner while maintaining maximal materialistic characteristics. Cloud-based technology processes many designs with different topologies and characteristics at the same time. After the generative design, the structure is checked to see if it meets the goals stated by the parameter and structural criteria. If the restrictions are not met, the design will be rejected [166]. A streamlined GUI offers the stages in linear order aids the user in completing all of the steps [167]. Supervised learning is particularly useful for engineering design optimization and exploration since it makes mapping out feasible zones much easier [168] [169].

A quad copter system is made up of numerous parts that are mostly attached to the frame. Different classes of components are added to make representation easier, with each class having its own set of specific descriptive characteristics that may be provided by the user or produced automatically if a hardware part is picked from the library.

The block diagram as presented in figure 5.2 of quad copter which consists of Flight controller. Attitude Flight Stabilization System (AFSS) consists of 3-axis accelerometer and gyroscope in built of flight controller. An electronic speed control (ESC) is a circuit that regulates and controls the rotational speed of an electric motor. It may also provide motor reversing and dynamic braking.

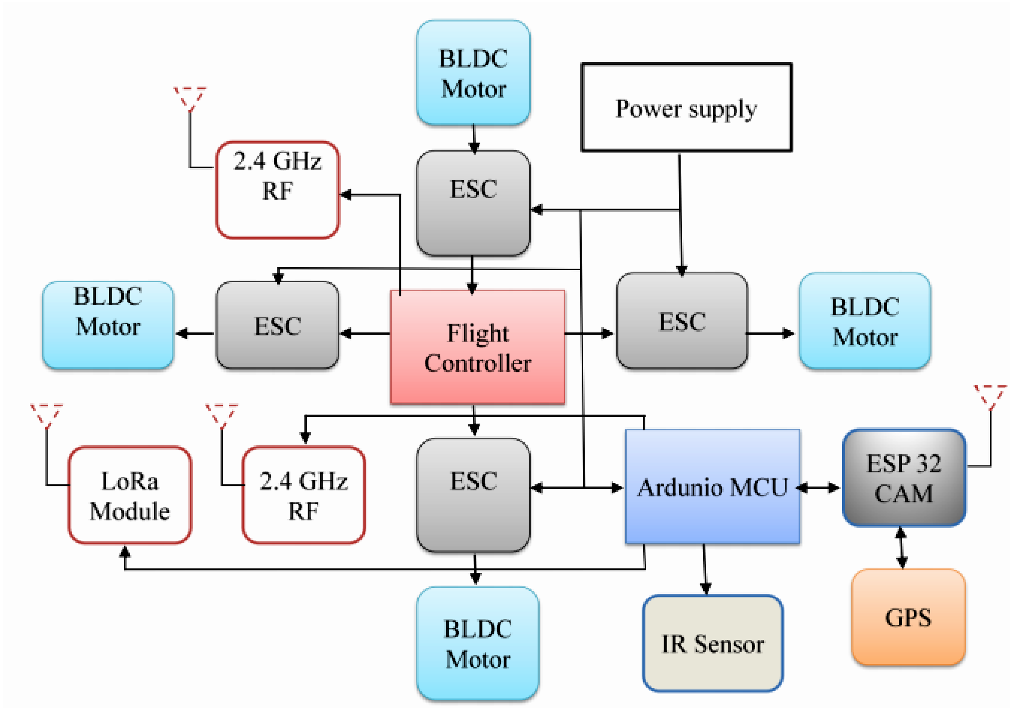



Figure 5.2 Block diagram of quad copter

Brushless Direct Current (BLDC) motors are commonly used as rotors in quadcopter drones due to their great efficiency and small size. For drone position and velocity control, the BLDC motor speed control is critical. Lithium-ion polymer batteries (LiPo) are often constructed up of a number of identical secondary cells connected in series to optimise discharge current, and they are sometimes offered in packs to maximize the total accessible voltage. Figure. 5.3 shows the various dimensions considered for the structure of the quadcopter. The bar distribution takes a length of 120.5mm with four bars and the width is 8.9mm. Whereas the base plate shows the length is 101mm in square shape. The total length of the quadcopter with measurement of two end-to-end bar lengths is 342mm. the adjacent of two bars length is taken 254mm. The components are categorized as follows. Batteries and the electronic controller power module are all included in this category. The electronics components like ESP32 cam, Global positioning system (GPS), 2.4GHz RF modules, and LoRa communication module.

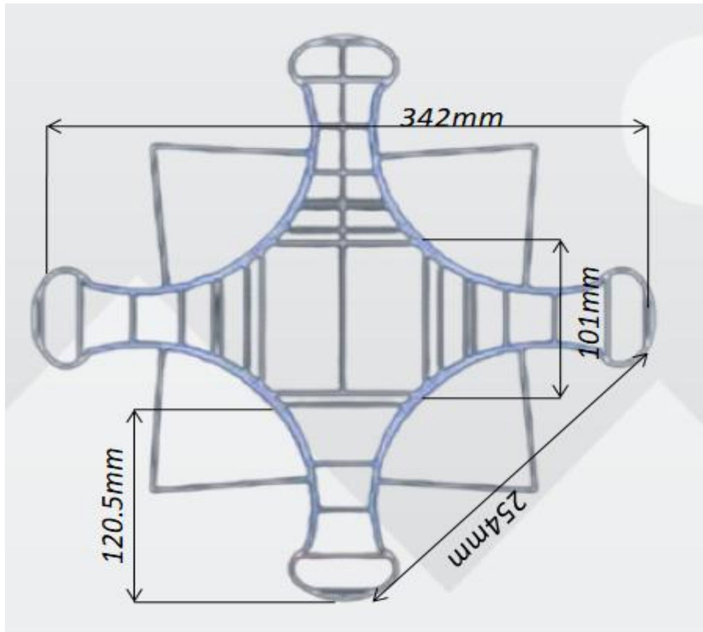



Figure 5.3 Structure dimensions

### 5.3 Simulation Model of Quadcopter

Drones are complex assemblies with many components; therefore, they cannot be handled as individual components, and they must be simulated with all of the different elements in the system with the assembly in consideration. The load conditions used in the simulation are provided in this way to help identify the components that are under the most stress and displacement aids in drone design. The drone is given stress and displacement to accomplish a stable landing and avoid damage. The less weight of components will raise the drone easily.

Minimum displacement of bar noticed 0.005mm at 0.5 inch of the curve length and near the edge of the bar, a maximum displacement of 0.105mm at 4.7 inch of the curve length was measured, which may not have a major impact on quad copter stability as shown figure.5.4.

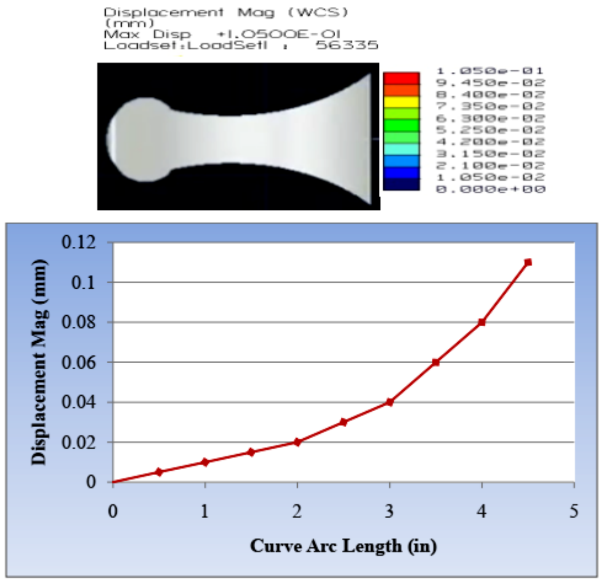



Figure 5.4 Bar displacement distribution and Displacement of Bar

The minimum stress of bar observed is 18MPa at 4.7 curved arc length. At a position where the bar was to be connected, the maximum Von Mises stress was found to be 127MPa at beginning of the curve length from figure.5.5.

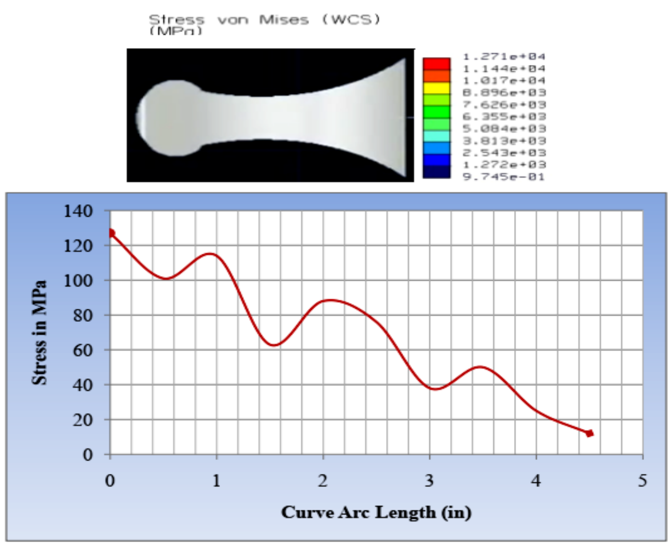



Figure 5.5 Bar Stress distribution and stress of Bar

The minimum displacement base plate noticed 0.001mm at 2.2 inch of the curve length and Near the edge of the bar, a maximum displacement of 0.02 mm at 4 inch of the curve length was measured, which may have a major impact on quad copter stability as shown figure.5.6.

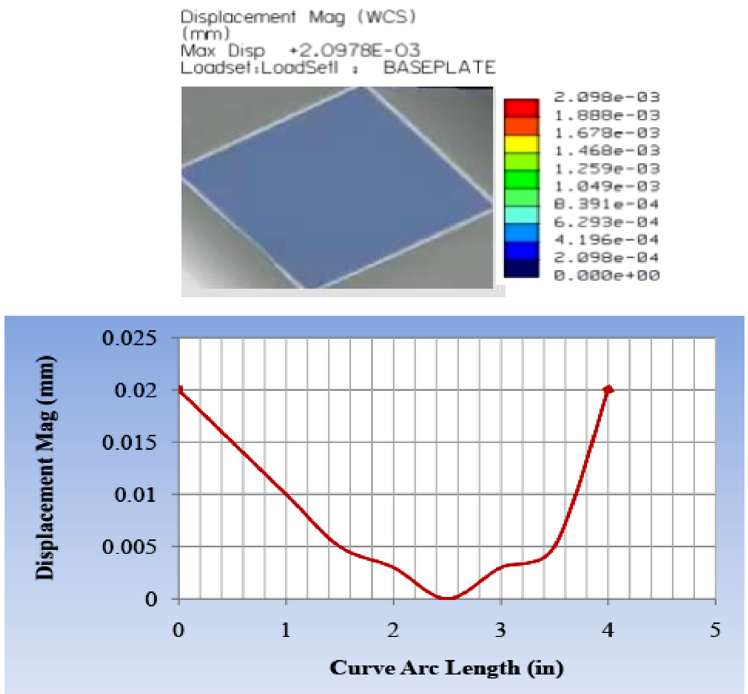



Figure 5.6 Base plate displacement distribution and displacement of base plate

The minimum stress of base plate noticed 10MPa at 4 inch of the curve length and At a position where the base plate was to be connected, the maximum Von Mises stress was found to be 280MPa at 1.5inch of the curve length from figure.5.7.

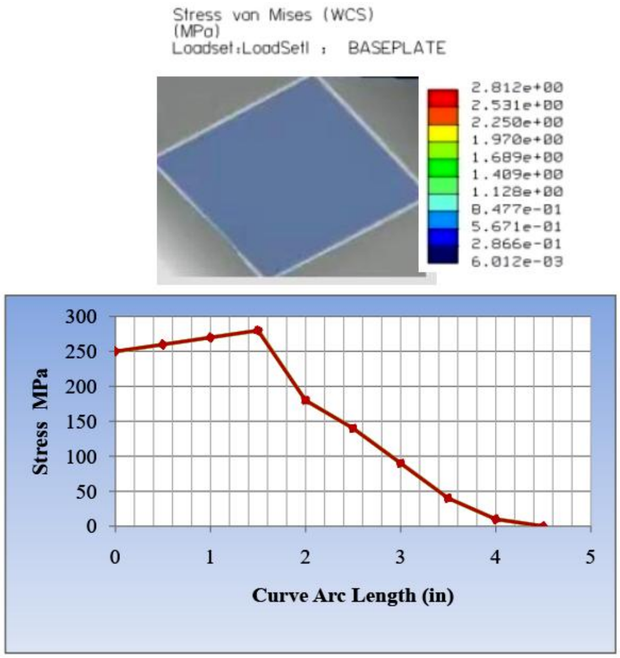



Figure 5.7 Base plate stress distribution and stress of base plate

The minimum displacement for structure of drone noticed 0.002mm at 1 inch of the curve length and near the edge of the bar, a maximum displacement of 0.019 mm at 4 inch of the curve length was measured as shown figure.5.8.

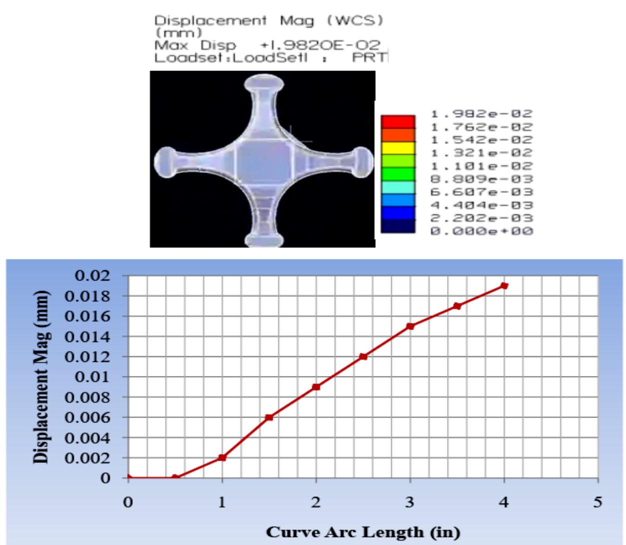



Figure 5.8 Structure displacement behavior and displacement of structure

The minimum stress noticed structure is 2MPa at 4 inch of the curve length and at a position where the base plate was to be connected, the maximum Von Mises stress was found to be 23.2 MPa in figure.5.9.

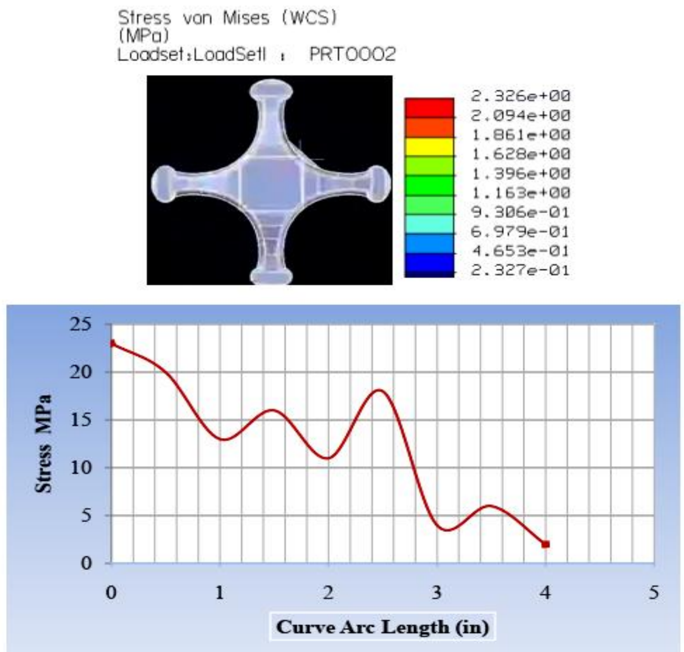



Figure 5.9 Structure Stress behavior and stress of structure

The following conclusions can be drawn from the simulations. Near the edge of the bar, and base plate a maximum displacement of 0.105mm, 0.02is measured, which may not have a major impact on quad copter stability.  At a position where the bar, base plate was to be connected, the maximum Von Mises stress was found to be 127MPa and 280MPa. As a result, after inspecting different factors on the base and bar plate, it became clear that the structure's weight needed to be decreased even more to prevent failure. Figures 5.8 and 5.9 of the structural analysis, the motor mount have the displacement, which is 0.019mm. According to the results, the model has a very minimal amount of displacement. The arm has a minor displacement, indicating that it is safe, and there is no substantial displacement, indicating that our design is safe based on these data. The maximum stresses developed in the structure are 23.2 MPa, while the yield stress value for ABS plus plastic as materials used in the simulation is 42-45 MPa which is in permissible limit, indicating that the framework will not be affected in the event of an increase in the component's weight, as well as from a sudden landing or crashing. Figure. 5.10show the final structure of CAD model of quadcopter designs in AutoCAD software.

Figure 5.10 CAD model of quadcopter

This mechanism was deemed the most crucial for the Quad Copter's steady flying. Its primary parts and system components were acquired with known specifications from open market sources. Flight controllers FY-90 are the finest for controlling quadcopter. It includes an inbuilt 3-axis gyroscope and 3-axis accelerometer, and the input voltage ranges from 4 to 6 volts with 52mA of current. Figure.5.11 shows the flight controller. When in full balancing mode, it detects any changes in the model's horizontal attitude. If an attitude change has occurred, the device will transmit signals to the Quadcopter motors to modify their rotating speed in order to maintain stability.

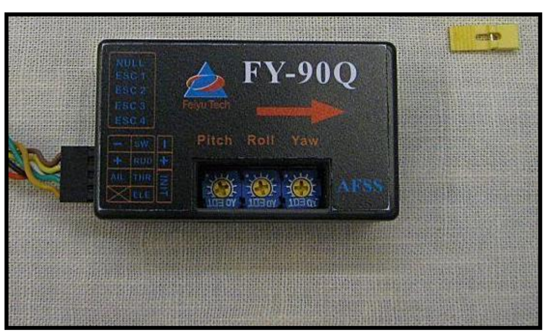



Figure 5.11Flight stabilization system

The IS 45A electronics speed controller (ESC) is responsible for managing the speed of the quadcopter's electric motors. The input voltage ranges from 5 to 7 volts. Figure 5.12 presents the IS 45A electronic speed controller.

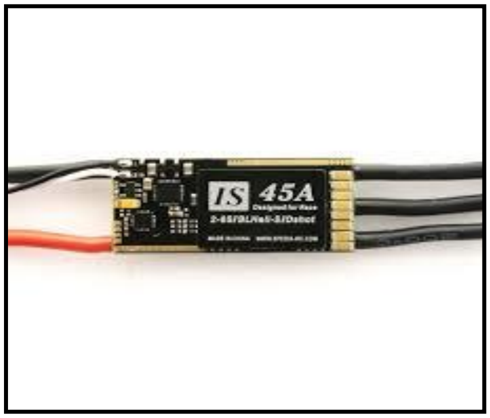



Figure 5.12 Electronic speed controllers

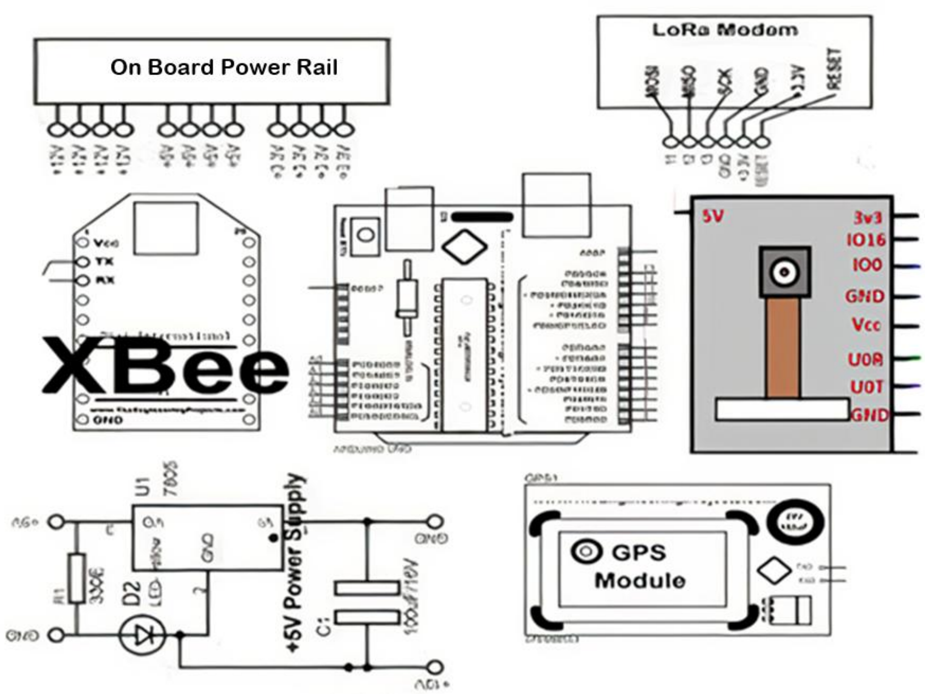



Figure 5.13 Circuit design of electronic components

The circuit connections of various electronic components used in drone are as follows

- The Vcc, GND, and OUT pins of the IR proximity sensor are connected with +5V, GND, and 7 pins of the Ardunio.
- The Vcc, GND, and TX and Rx pins of the GPS module are connected with+5V, GND, 2 and 3 pins of the Ardunio.
- The Vcc, GND, and TX and Rx pins of the Zigbee module are connected with 3.3V, GND, 4 and 8 pins of the Ardunio.
- The Vcc, GND, and TX and Rx pins of the LoRa module are connected with 3.3V, GND, 12 and 13 pins of the Ardunio.
- The Vcc, GND, and TX and Rx pins of the ESP 32 cam module are connected with 3.3V, GND, 0 and 1 pins of the Ardunio.
- Battery +12V to +5V convertor is connected to +Vcc and GND pins of the Ardunio.

Ardunio is a hardware device having a microcontroller, power supply, memory, and other electronic devices inbuilt. It is a programmable device with both hardware and software. It can be interfaced with various IoT sensors and components and interact with surroundings.

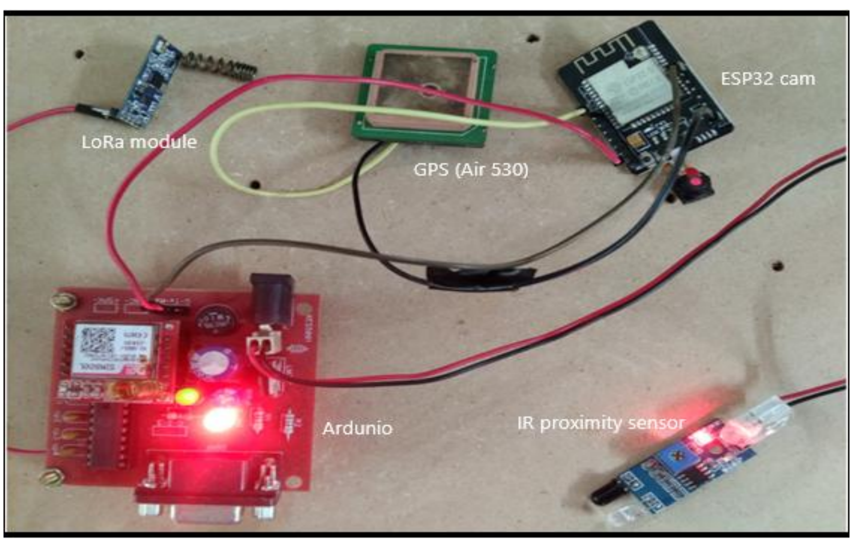



Figure 5.14 Electronic components of drone

The ESP32-CAM is a small, low-power camera module based on the ESP32 microcontroller. It features an OV2640 camera and a TF card slot onboard with intelligent IoT, including wireless video monitoring, Wi-Fi picture upload, and so on. GPS (Global Positioning System) modules are made up of small computers and antennas that receive data directly from satellites through specialized radio frequencies. It will then get timestamps from all visible satellites, as well as other information. GPS (Air530). It's a multi-mode satellite positioning and navigation module with outstanding performance and integration as shown in figure 5.14. Proximity detection sensors detect the presence of an object by measuring reflected infrared (IR) radiation. Figure.5.15 shows the assembled quadcopter drone. IR proximity detection sensors can be used to detect the line of sight of the pipeline. Zigbee is a low-cost, IoT communication protocol that was designed as an open worldwide standard. IEEE 802.15, the Zigbee standard, is used.

Figure 5.15 Final Assembly of parts of systems

The working of the drone is mainly for on-demand visual collection. Whenever the pipeline parameters show abnormal values, the monitoring section will send an alert to SOC and drone yard via the 2.4 GHz module. After receiving the alert, the Drone is activated and starts pipeline inspection and the status of the drone is sent to the end-user via LoRa communication. The ESP32 Wi-Fi camera module interfaced with the GPS module plays important role in collecting video, latitude, and longitude display the end-user. Here IR proximity sensors can be used for obstacle (Pipeline) sensing when drones started inspecting pipeline communicated to end-user via LoRa. Individual component and final assembly take-off weights were also measured, as represented in the figure 5.16. Propellers 5x3, 1378KV motor with a speed of 17362 rpm were chosen according to our technique. Brushless motors require a significant amount of current. As a result, we chose a 3 cell 3300 mAh Li-Po battery with a 12.6 V Li-Po battery that can continuously produce a 3Amp current. A IS 45A ESC is used to control each of the brushless motors, ensuring that the appropriate current is always available to drive the motors.

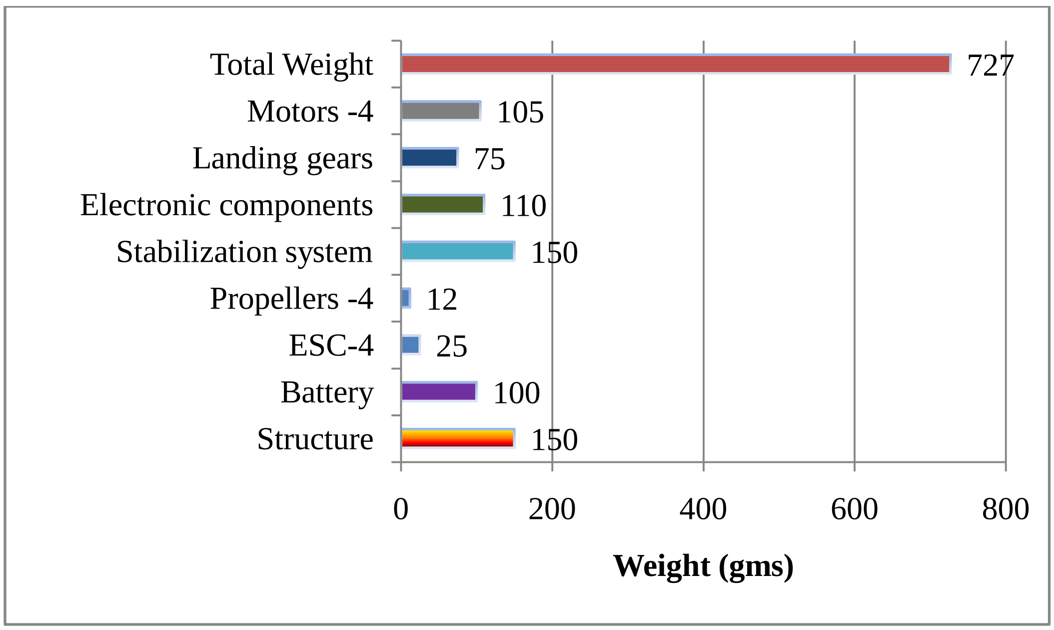



Figure 5.6 Takeoff weight of drone

The quad copter's final mass was measured at 727G from the table.5.16. The motors and propellers were projected to be sufficient to lift it to a height of over 8-10 meters, as intended. The longest flight was 20 minutes. Within the envelope of its adjustable height of 10 meters, the vehicle was able to properly acquire photos and send video. Figure.5.17 shows the step-by-step methodology of operation of the drone yard.

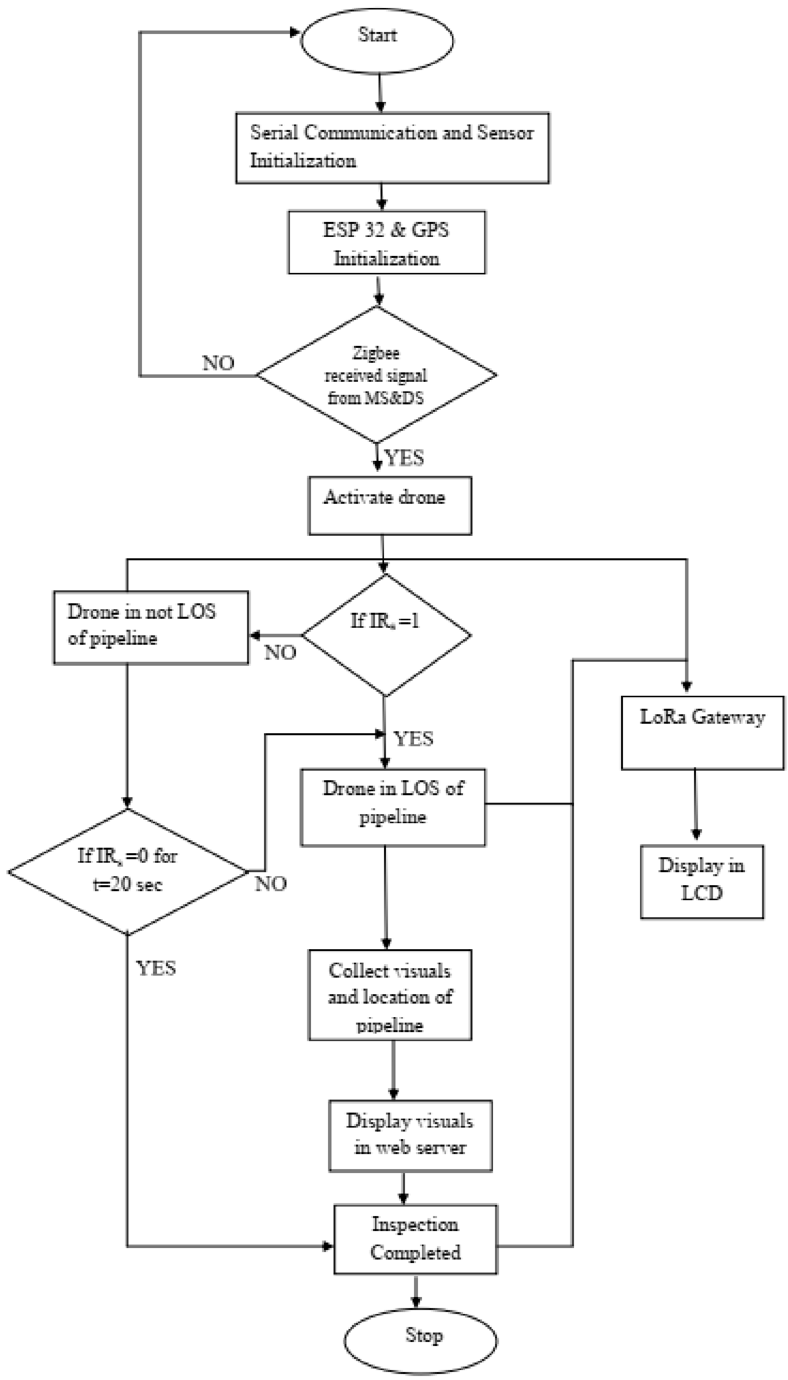



Figure 5.16Methodology of drone yard

### 5.4 Chapter Summary

This chapter summarizes the design of quadcopter drones based on the knowledge available through literature. Using AutoCAD software simulations are generated and for finalizing parameters displacement and stress of the bar, bar plate, and structure of the quadcopter, a design process was carried out and a quadcopter configuration was developed using various IoT components. It was able to perform pipeline monitoring surveillance from a height of 8-10 meters for 20 minutes.

# CHAPTER-6

# PERFORMANCE ANALYSIS

In this chapter data acquisition from field sensor nodes of the pipeline are analyzed with various cases and the algorithm is designed for pipeline leak finding. Moreover, power consumption analysis for various IoT components used in this work is discussed.

## 6.1 Data Acquisition

### 6.1.1 Case-I: Smooth transportation of Oil through pipeline

For smooth conduction of oil through the pipeline, some of the parameters are to be monitored effectively. The data acquired from the sensor nodes deployed in the oil pipeline field for collecting sensor data of parameters humidity, oil temperature, vibrations, pressure, and flow rate with RSSI. Sensory data for those metrics are collected and displayed in graphs using the ThingSpeak IoT cloud.

**a) Oil Temperature**

It is essential to pre-heat oil before transporting it through a pipeline to minimize fluid viscosity [91]. The temperature of the oil is regulated between 25$^0$C and 35$^0$C for smooth pumping [91]. Figure.6.1 shows the variations of the temperature while oil transportation through the pipeline. The graph shows the variations between 30$^0$C and 32$^0$C.

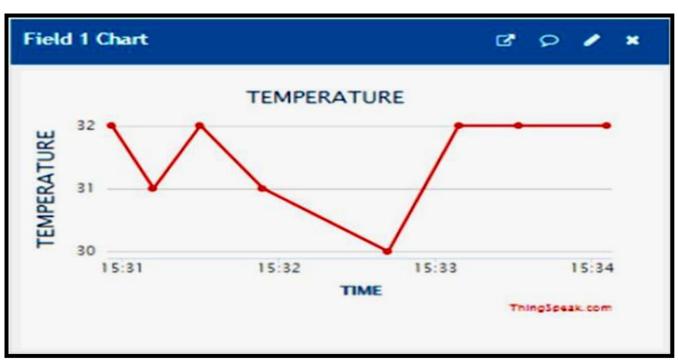



Figure 6.1 Oil temperature

**b) Pressure of the pipe**

The most important parameter in pipeline monitoring is pressure. It is highly essential to measure pipe pressure to ensure no leaks in the pipeline. Here 1.5" outer diameter (inch) and 0.5" inner diameter thermoplastic pipe is installed and the maximum pressure rating of the pipe is 1600 $KN/m^2$. Here pressure is measured in Kilo Newton per meter square. As shown in the figure. 6.2 variations of the pressure sensor values from a minimum 1545 $KN/m^2$ and a maximum of 1550 $KN/m^2$ are noticed using a pressure sensor.

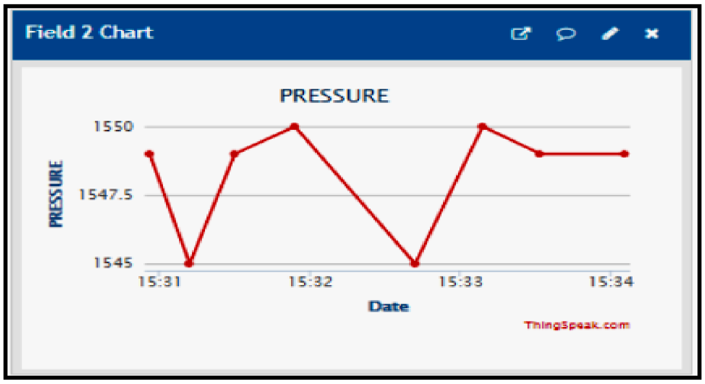



Figure 6.2 Pressure of the pipeline

**c) Flow rate**

Accurate flow measurement is a necessary stage for smooth maintenance of the pipeline. The flow rate range of the pipe is the maximum rate of 11.3 L/m and the minimum of 10 L/m. The variation is shown in the graph between 10 to 11 L/m from the flow rate sensor. As shown in figure 6.3. This sensor will generate pulses. Pulse frequency (Hz) / 7.5 = flow rate in Liters/minute.

Flow rate varies with diameter of the pipe as give in equation- 6.1[151] [152]

$$Q_w = 3600\pi \cdot v(\frac{d}{2})^2 \quad \text{-----}\blacktriangleright \qquad 6.1$$

Where $Q_w$ = Flow rate (L/m)

D= Outer diameter of the pipe (inch)

V= Velocity of the fluid (m/s)

π stands for Pi which is 3.14

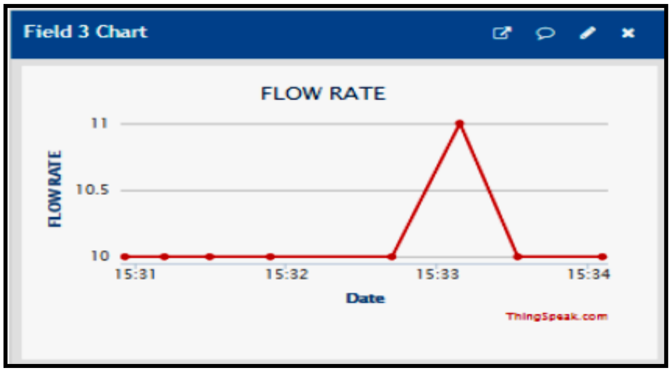



Figure 6.3 Flow rate of oil

The 1.5 x 0.5 inch diameter of the thermoplastic pipe has rating of dispatching liquid is 11.3 L/m with the velocity of 1.7 m/s. The table 6.1 represents the various flow rates of the pipe with diameters.

Table 6.1. Flow rate varying with diameter of the pipe

| **Outer Diameter (OD) inch** | **Inner Diameter (ID) inch** | **Flow rate (L/m)** |
|---|---|---|
| 1.5” | 0.3” | 2.5 |
| 1.5” | 0.5” | 11.3 |
| 1.5” | 0.7” | 28 |
| 1.5” | 0.9” | 45.2 |
| 1.5” | 1” | 66.8 |
| 1.5” | 1.2” | 84 |

d) **Humidity**

The humidity inside the pipeline is to be less to reduce corrosion issues. This parameter is useful in pipeline monitoring to check the moister level inside the pipeline before transporting oil. Before oil is transported through the pipeline, the moisture content must be less than 25%RH [75]. Figure 6.4 presents variations of humidity level inside the pipeline with a range of 19.5%RH to 20% RH. Where RH is the relative humidity.

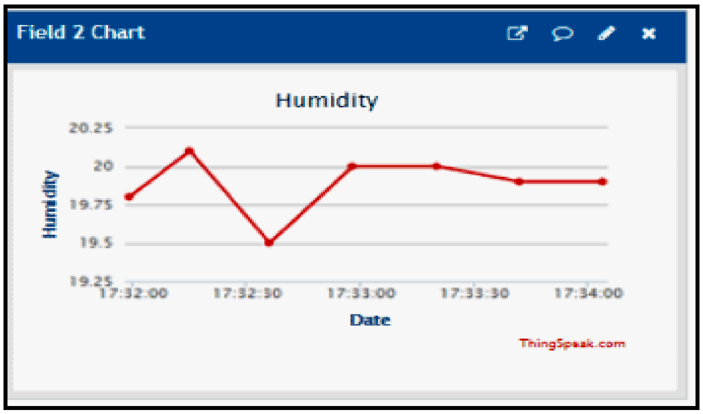



Figure 6.5 Humidity

**e) Received Signal Strength Indicator (RSSI)**

Received signal strength Indicator is a signal that represents the strength of the incoming signal to the gateway. Here we use the LoRa SX-1278 module to transfer data from pipeline field to gateway. The good strength of the RSSI of LoRa is -30dBm gives the strong signal and -120dBm gives the weak signal. Figure 6.5 presents average RSSI= -62 dBm, Effective data reception is achieved during experimental in the range of 1.5 to 2 km.

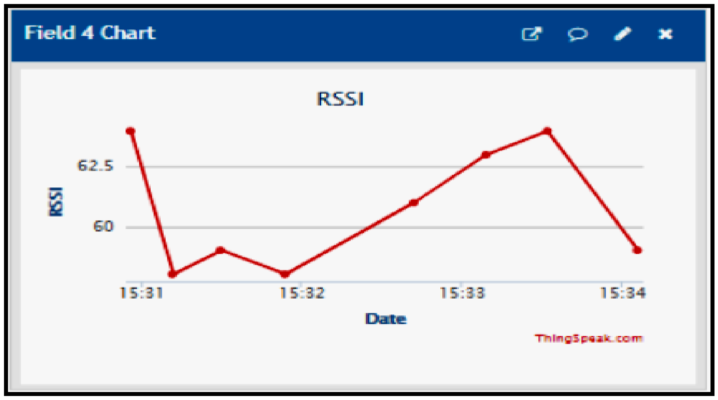



Figure 6.5 Received signal strength indicator

### f) ThingSpeak Dashboard for Case-1

All the parameters data acquired from pipeline field are communicated to gateway through LoRa. The ES8266 Wi-Fi module is embedded with gateway is used to upload data in ThingSpeak IoT cloud in graphical representation as shown in figure.6.6.

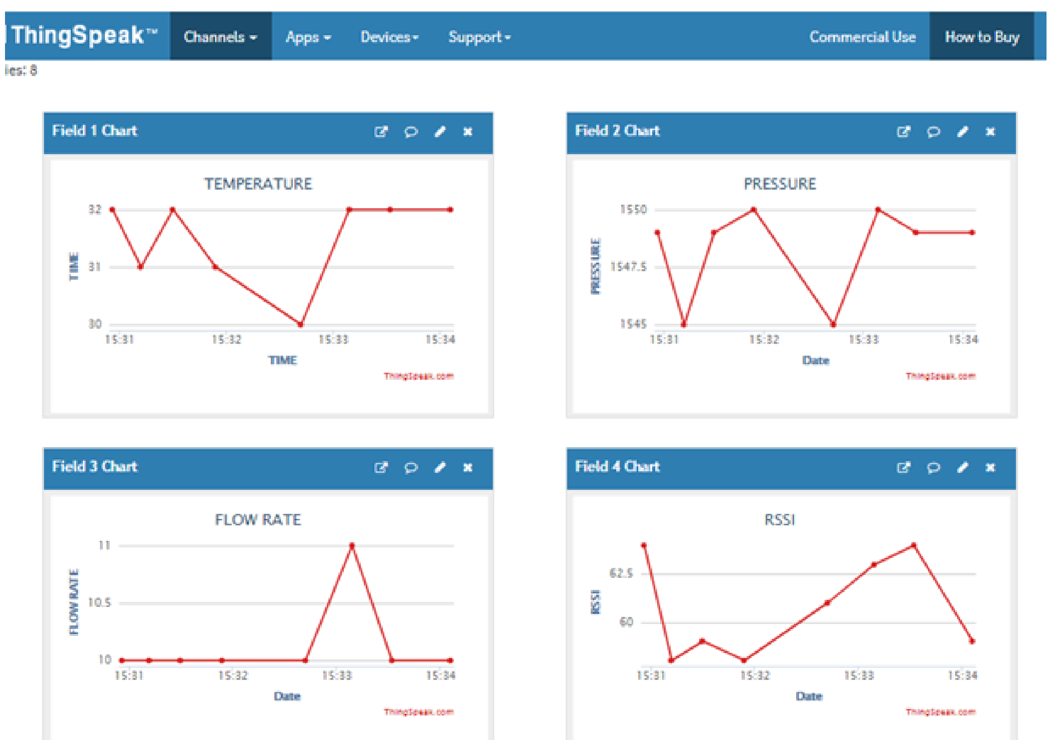



Figure 6.6. Parameters for Case-1

### 6.1.2 Case-II: Third-party Damage (TPD) on the Pipeline

Damage to pipelines committed by individuals or groups unrelated to the pipeline company is referred to as third-party damage (TPD). This damage is for theft of oil by drilling a hole into an oil pipeline as shown in figure.6.7 or natural damage caused by construction nearby pipeline. In this case, vibrations and acoustic waves are observed and analyzed due to the external force on the pipeline.

Figure 6.7.Third-party damage on pipeline

**a) Acoustic Analysis**

The acoustic sensors are used to sense the third-party damage and leak of the pipe noise. The LM393 acoustic sensor intensity range is 40dB to 159dB. Here three stages of acoustic analysis is carried out.

Intensity is defined to be the power per unit area carried by a wave equation-6.2 [80].

$$I = \frac{P}{A} \quad (6.2)$$

Where *P* is the power through an area *A with* $W/m^2$

The intensity of sound wave related to equation - 6.3

$$I = \frac{(\Delta p)^2}{2\mu v_w} \quad (6.3)$$

$$\frac{(0.656pa)^2}{2(1.29kg/m^3(331m/s))} \quad (6.4)$$

Here Δp is the pressure amplitude (Pascal's)

The sound intensity level β in decibels of a sound having an intensity I in watts per meter squared is given equation-6.5.

$$\beta(dB) = 10\ log(\frac{I}{I_0}) \quad (6.5)$$

$I_0 = 10^{-12}$ W/m$^2$ is a reference intensity.

**Level-I:** The intensity of sound is achieved 43dB (Decibels) as shown in figure.6.8 from100mts of distance of the pipeline damage and the atmospheric pressure of the damage sound lies at 0.402pa.

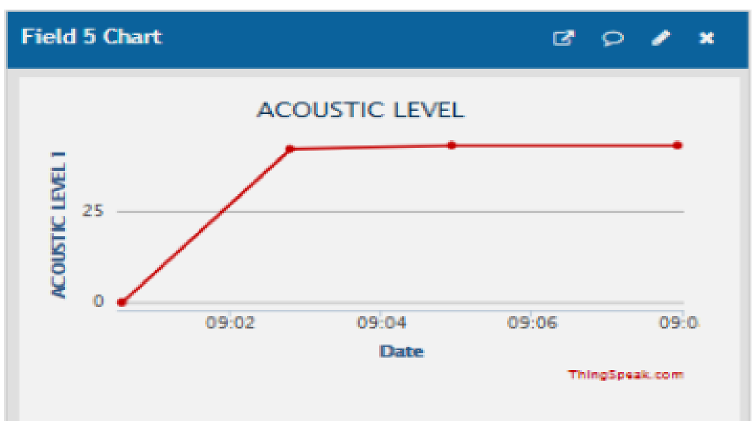



Figure 6.8. Acoustic signals at Level –I

**Level-II:** The intensity of sound is achieved 87dB as shown in figure 6.9 at 50mts distance of pipeline damage, where the atmospheric pressure of the damage sound lies at 0.656pa.

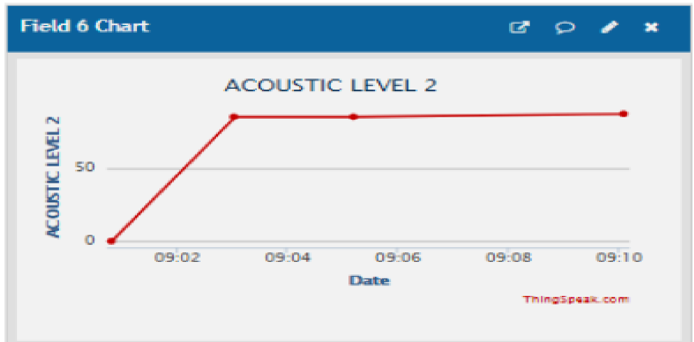



Figure 6.9. Acoustic signals at Level –II

**Level-III:** The intensity of sound achieved 120dB as shown in figure 6.10 from 1 mts distance of the pipeline damage and the atmospheric pressure of the damage sound lies at 0.925pa.

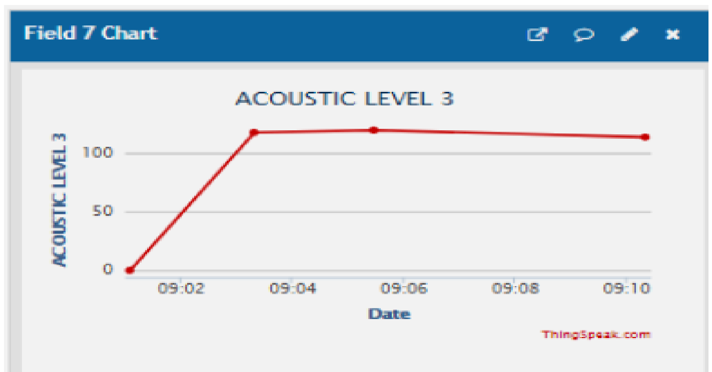



Figure 6.10 Acoustic signals at Level –III

**b) Vibration Analysis**

Vibration sensor plays a prominent role in detecting third-Party damages of the pipeline. The sensitivity range of sensor is 50-250Hz. The vibrations of the pipe depend up on pipe parameters.

The natural frequency of empty and loaded pipes is given equation-6.6 [83]

$$f_n = \frac{1}{2\pi} \cdot 22.4 \cdot \sqrt{\left[\frac{EI}{\mu L^4}\right]} \tag{6.6}$$

$f_n$ = Natural frequency of the pipe (Hz)

$E$ = Young's modulus of elasticity

$I$ = moment of inertia for the pipe (0.049*[$OD^4$-$ID^4$]) in inches or meters

$\mu$ = mass per unit length of the pipe lbs/inch or kg/m

$L$ = distance between pipe supports (inches or meters)

Weight of liquid in pipes per unit length in equation- 6.7.

$$\mu_l = \rho_l A_i \qquad (6.7)$$

$$= \rho_l \pi (d_i / 2)^2$$

$$= (\pi / 4) \rho_l d_i^2$$

Weight of empty pipe per unit length in equation-6.8

$$\mu_e = \rho_m A_m (6.8)$$

$$= \rho_m \pi (d_o^2 - d_i^2) / 4$$

$$= (\pi / 4) \rho_m (d_o^2 - d_i^2)$$

Weight of pipe with liquid equation-6.9

$$\mu = \mu_e + \mu_l (6.9)$$

$\mu_p$ = weight of empty pipe per unit length (kg/m, lb/in)

$\rho_m$ = density of pipe material (kg/$m^3$, lb/$in^3$)

$A_m$ = cross-sectional wall area of pipe *($m^2$, $in^2$)*

$d_o$ = outside diameter (m, in)

$d_i$ = inside diameter (m, in)

t = wall thickness (m, in)

$w_l$ = weight of liquid in pipe per unit length of pipe (kg, lb**)**

The Natural frequency of pipes with various moment of inertia with inner and outer diameter of pipe is shown in table 6.2. Moment of inertia for 1.5” x 0.5” pipe is $(0.049*[OD^4-ID^4]) = 0.000097$ Kg.m$^4$

Table 6.2Natural frequency of pipes with various moment of inertia

| **Inner Diameter (ID) inch** | **Outer diameter (OD) inch** | **Moment of inertia (MOI) Kg.m$^4$** | **Natural frequency of Empty pipe (Hz)** | **Natural frequency of Loaded pipe (Hz)** |
|---|---|---|---|---|
| 1.5” | 0.3” | 0.000086 | 36 | 28 |
| 1.5” | 0.5” | 0.000097 | 42 | 34 |
| 1.5” | 0.7” | 0.000106 | 48 | 39 |
| 1.5” | 0.9” | 0.000118 | 52 | 43 |
| 1.5” | 1.2” | 0.000127 | 57 | 46 |

According to the parameters of pipe 1.5” x 0.5”, the natural frequency of empty pipe and loaded pipe is $f_n$ =42  Hz, 34 Hz.

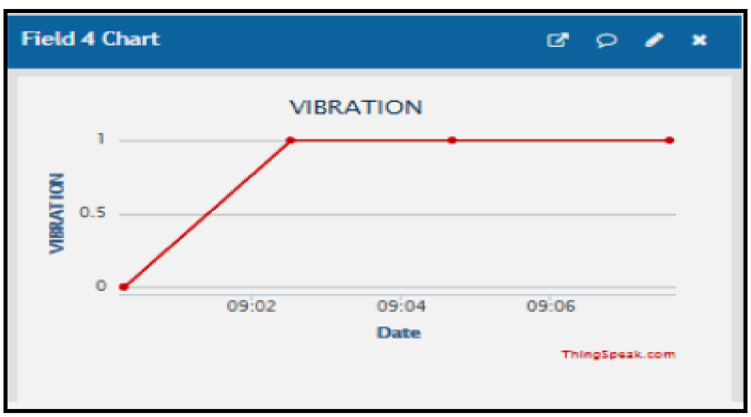



Figure 6.11 Vibration of the pipe

The vibrations obtained as shown in figure.6.11are abnormal than natural frequency of pipe. For applied force vibrations, the sensor sets the output value to ‘1‘where the frequency is >50Hz.

### c) Pressure and Flow rate

It is observed from the graph the pressure variations range1555KN/m$^2$ – 1572 KN/m$^2$ and the flow rate noticed is 10.4-10.8 Lit/m from the figure 6.12 & 6.13 which are in threshold range. Table 6.3 presents the summary of case-II data analysis.

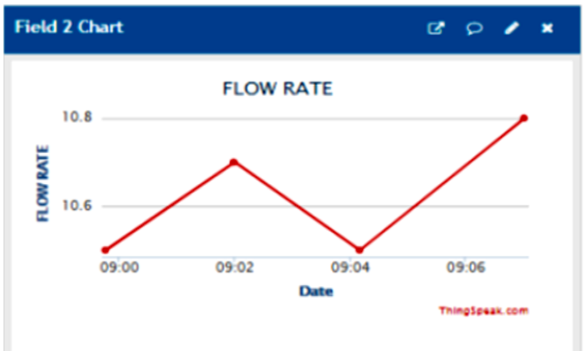



Figure 6.12. Flowrate

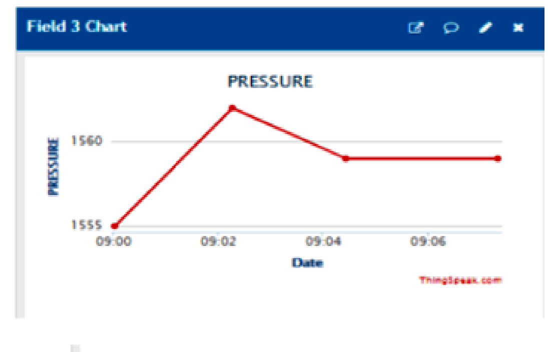



Figure 6.13. Pressure

Table 6.3 Summary of Case-II data analysis

| Parameter | Threshold Range | Observed values |
|---|---|---|
| Temperature | $25^0$ C to $35^0$ C | $32^0$ C to $33^0$ C |
| Pressure (KN/m$^2$) | 1500 KN/m$^2$ - 1600 KN/m$^2$ | 1555 KN/m$^2$ - 1572 KN/m$^2$ |
| Flow rate (L/m) | 10-11 Lit/m | 10.4-10.8 Lit/m |
| Vibration (Hz) | 34 Hz | >50Hz |
| Acoustic (0-1mts) | 40dB to 159dB | 120dB, 0.925pa |
| Acoustic (50mts) | | 87dB, 0.656pa |
| Acoustic (100mts) | | 43dB, 0.402pa |

From the above analysis it was observed that while third-party damage happening to the pipe. The vibration and acoustic sensors are excited and noticed abnormal values. The temperature, pressure, flow rate are in the threshold range. But vibrations noticed (>50Hz) which is not in threshold range. Moreover, Acoustic analysis is carried out in three stages varying with distance of acoustic sensor from the damage point of the pipeline. It is observed that sensor distance increases, the intensity of sound and atmospheric pressure is gradually decreased (120dB-43dB).

### ThingSpeak Dashboard for Case-II

All the parameters data acquired from pipeline field are communicated to gateway through LoRa. The ES8266 Wi-Fi module is embedded with gateway is used to upload data in ThingSpeak IoT cloud in graphical representation as shown in figure 6.14.

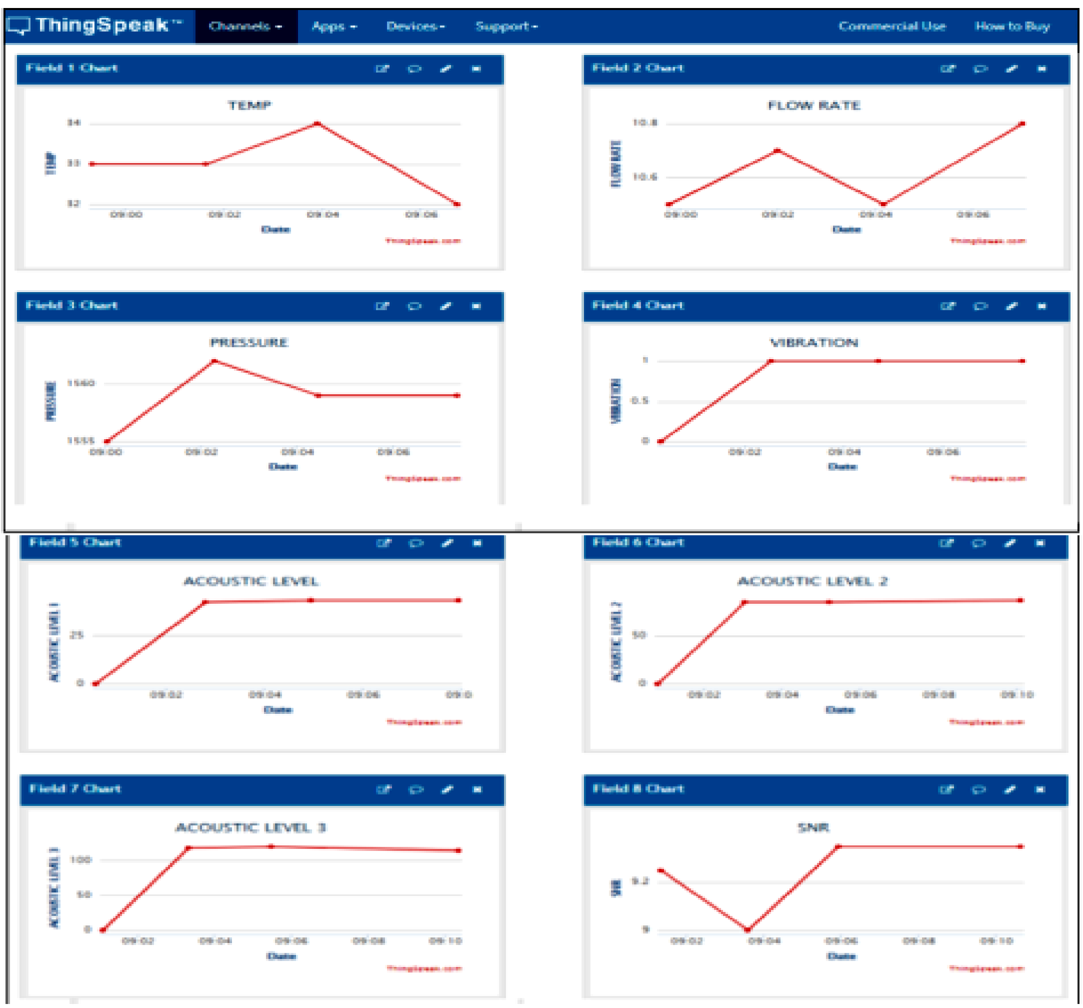



Figure 6.14 ThingSpeak dashboard of Case-II

**Damage Localization using ESP32 Web server**

A Web Server is hardware and software combination that keeps track of, fetches, and serves web pages to Web Clients. The content on web sites can be in any format, including text in HTML documents, images, video, and applications, among others.

A web page in the form of HTML Text must be present on the ESP32 Web Server. The ESP32 Wi-Fi cam module connects to a Wi-Fi network using the SSID and Password, and the router provides the ESP32 Wi-Fi cam Module a local IP addresses. When you open the Serial Monitor in the Ardunio IDE, the ESP32 Module will print essential information including the Wi-Fi connection status, IP Address, and Web Server URL. Type the IP Address of ESP32 into a Web browser on a computer or a mobile phone. A web page provided by the ESP32's Web Server should be accessible.

Here ESP 32 Wi-Fi camera module interfaced with GPS in drone will take the visuals of the pipeline and communicate to the user along latitude and longitude data displayed in ESP32 web server. In this case the IP address of ESP32 is 192.168.0.105. Figure 6.15 shows the localization of damage by third-party using ESP 32 web server with latitude and longitude.

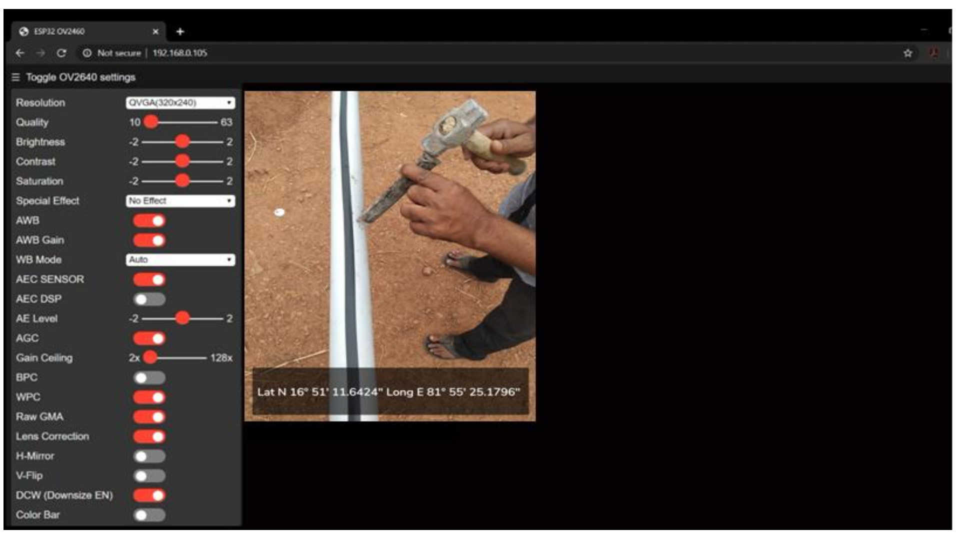



Figure 6.15 Damage localization using Drone

### 6.1.3 Case-III: Leak due to Third party damage

This case mainly focuses on pipe leak. Here Flow rate, pressure, vibrations and acoustic waves are observed due to pipe leak as shown in figure.6.16.

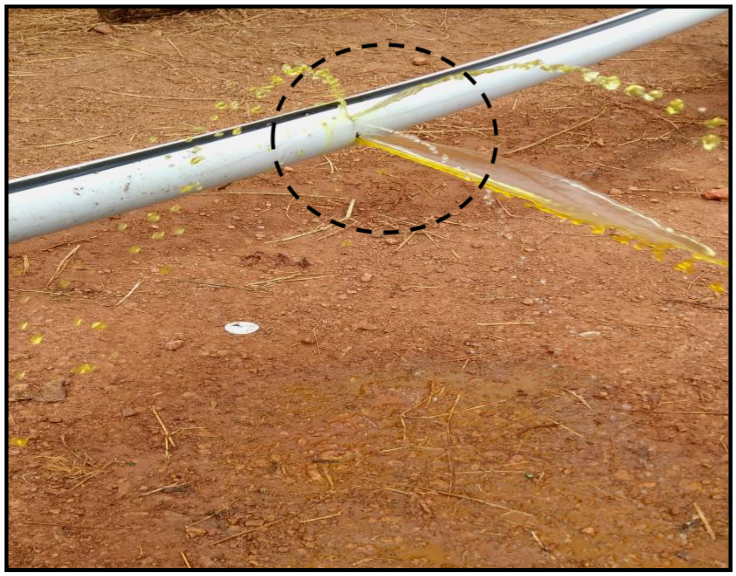


Figure 6.16Pipe Spills due to damage

**a) Flow rate and Pressure**

The relationship between the pressure drop across a pipeline and the flow rate through that pipeline is given from Bernoulli equation-6.10 [89].

$$TE = z + \frac{v^2}{2g} + \frac{144p}{u} \quad (6.10)$$

$$H_L = f\frac{L}{D}\frac{v^2}{2g} \quad (6.11)$$

$$dP = \frac{uH_L}{144} \quad (6.12)$$

The Darcy friction factor, f, takes into account the diameter, fluid viscosity is equation-6.13

$$dP = 2.161 * 10^{-4}\frac{(fLuQ^2)}{d^4} \quad (6.13)$$

f = Darcy friction factor (dimensionless)

L = pipe length (feet)

D = pipe inside diameter (feet)

v = fluid velocity (ft/sec)

g = gravitational constant

After the pipe leak as shown in figure.6.17& 6.18, the flow rate is gradually reduced to 10.6 Lit/m -7.2 Lit/m and pressure gradually decreased from as shown in figure 1554 to 825KN/m$^2$. The flow rate is reduced around 3.8 Lit/m which is 34% of actual flow and pressure of the pipe is declined to 729 KN/m$^2$ which is 46.4% of actual pressure of the pipe handled is observed.

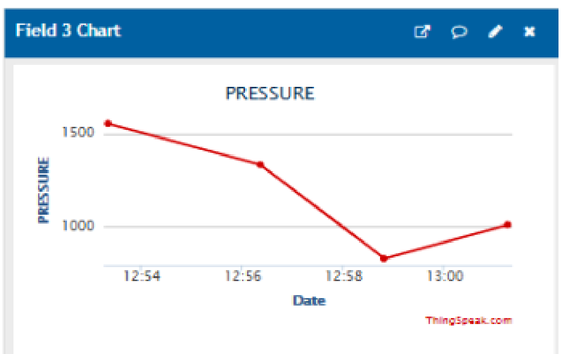



Figure 6.17Pressure

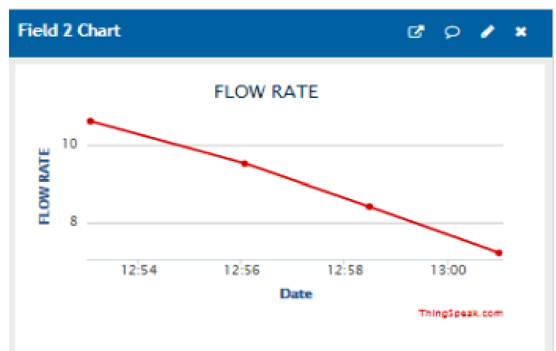



Figure 6.18Flow rate

**b) Vibration and Acoustic**

The vibrations obtained due to leak as shown in figure.6.19 are abnormal than natural frequency of pipe .the sensor sets the output value to '1' where the frequency lies between >50Hz.

External sound received while damaging pipeline is shown in figure.6.20. The intensity of sound is achieved 42dB of the pipe leak and atmospheric pressure of the leak sound 0.392pa at 50mts distance of pipeline damage.

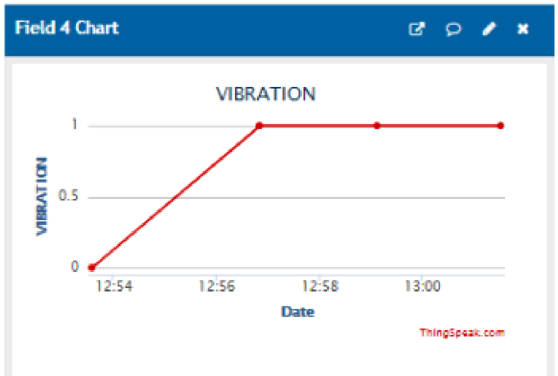



Figure 6.19 Vibrations

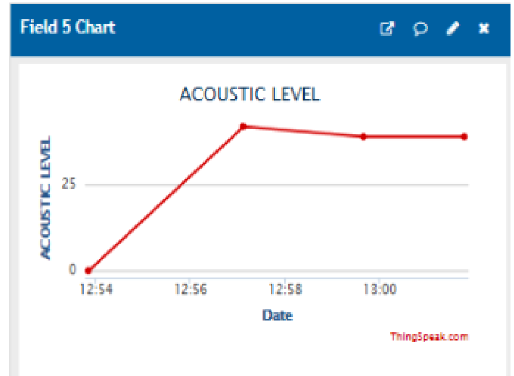



Figure 6.20 Acoustic waves

**c) Pressure analysis using Cayenne based Cloud**

The pressure pulse created by the pipe during damage is the basis for the mathematical model used in this study. The pressure pulse spreads in either direction from the site of the breakage, and when it reaches the oil pipeline's edges, it is reflected. The generated data of pulses in a pipeline, as well as sensor locations along the pipe, can be used to monitor a pipe and pinpoint an event's position. As indicated in figure 6.21, the occurrences occur as a result of penetration or exploding.

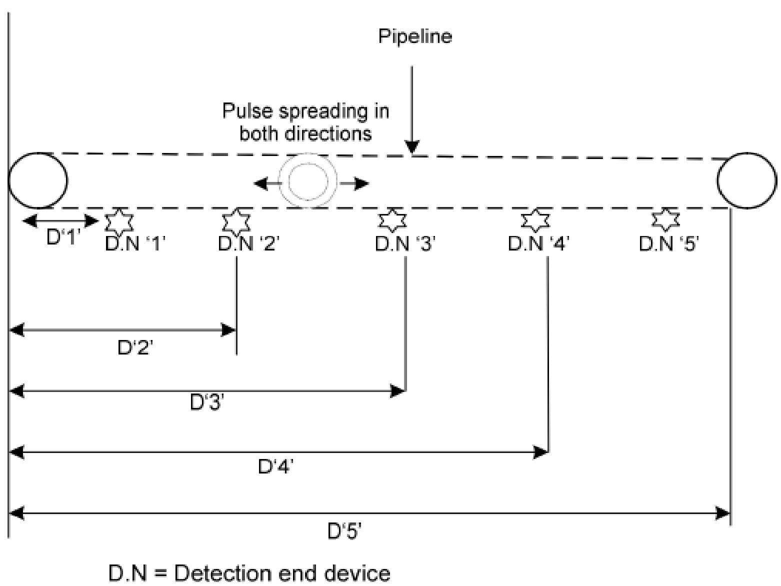



Figure 6.21 Schematic representation of detection end device placement

Figure 3 shows how the five-detection end devices (D.N 1 to D.N 5) are placed on the pipeline to identify the event's position. D1, D2, D3, D4, and D5 are the distances represented. t1, t2, t3, t4, and t5 are the five sensors that capture the arrival times of certainly created pulses induced by a disruptive incendiary event beginning at an uncertain point. Equation-6.14 & 6.15 is used to determine the specific location of the damage event from the sensor of D.N 2 and D.N 3.

$$y_{DE2} = \frac{\left(t_{23C_p+D32}\right)}{2} \qquad (6.14)$$

where $t_{23}$ indicates the time delay between arrival times of the sensor

$D_{32}$ indicates the distance between sensor 3 and sensor 2

*Cp* indicates the velocity of pressure

$$y_{DE3} = \frac{\left(D32 - t_{23C_p}\right)}{2} \qquad (6.15)$$

The pressure value of the pipeline as measured by the various detecting end devices is shown in Figure 6.22 of the Cayenne dashboards. The pipe can withstand a maximum pressure of 1600 KN/m$^2$. The pipeline pressure measurements are displayed on the dashboard, and it can be seen that Node0 and Node1 have constant pressure values. However, the pipeline's pressure is dropping below the threshold number at three different sites. Node 2, node 3, and node 4 all showed a steady drop in pressure. Table 6.4 presents the summary of case-III data analysis.


Figure 6.22 Cayenne dashbord

Table 6.4 Summary of Case-III Data analysis

| **Parameter** | **Threshold Range** | **Observed values** |
|---|---|---|
| Temperature | $25^0$C to $35^0$C | $32^0$C to $34^0$C |
| Pressure (KN/$m^2$) | 1500 KN/$m^2$ - 1600 KN/$m^2$ | 1554 KN/$m^2$ to 825KN/$m^2$ |
| Flow rate (L/m) | 10-11 Lit/m | 10.6 -7.2 Lit/m |
| Vibration (Hz) | 34 Hz | >50Hz |
| Acoustic (0-50mts) | 40dB to 159dB | 42dB, 0.392pa |

From the above analysis it is noticed that, four parameters of the pipeline Pressure, Flow rate, vibration, Acoustic are beyond the threshold range when pipe leaked due to damage. The flow rate is reduced around 3.8 Lit/m which is 34% of actual flow and pressure of the pipe is declined to 729 KN/$m^2$ which is 46.4% of actual pressure of the pipe can handle. The vibrations are above 50Hz of frequency and acoustic waves are noticed within the range of 50mts of the pipe leak.

**ThingSpeak Dashboard for Case-III**

All the parameters data of case-III acquired from pipeline field are communicated to gateway through LoRa. The ES8266 Wi-Fi module is embedded with gateway is used to upload data in ThingSpeak IoT cloud in graphical representation as shown in figure 6.23.


Figure 6.23 ThingSpeak dashboard of Case-III

**Pipe Leak Localization using ESP32 Web server**

Figure 6.24 shows the localization of pipe leakage using ESP 32 web server with latitude and longitude.

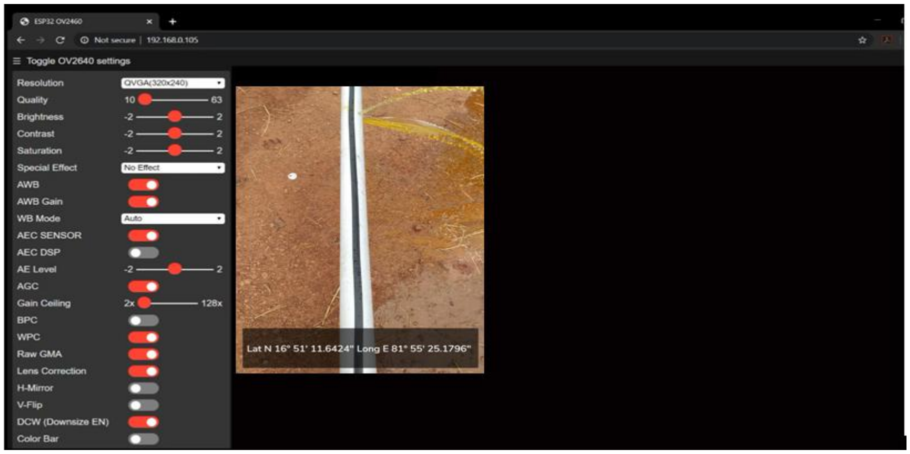



Figure 6.24 Leak Localization Using Drone

The evaluation of oil pipeline monitoring is performing by deploying the sensor nodes, drone, SOC and gateway in a real-time environment is shown in figure 6.25.

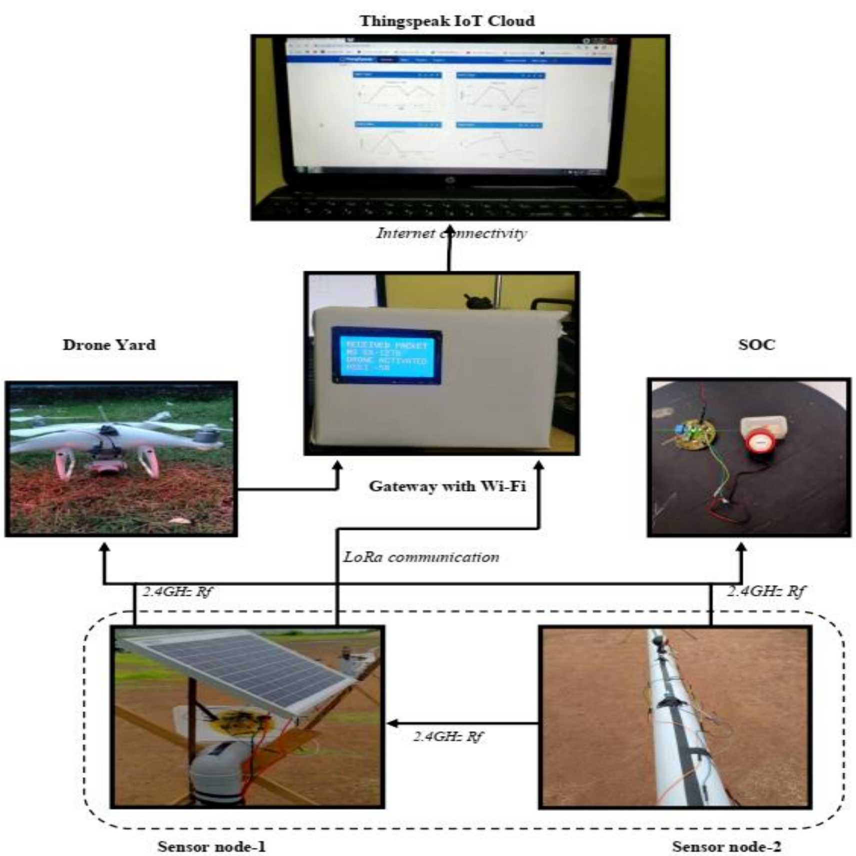



Figure 6.25 Experimental setup

### 6.2 Algorithm for Monitoring Oil Pipeline

From the algorithm it was observed that monitoring pipeline and leak finding process. Line 1-12 gives the process of monitoring section (MS) with pressure (Pr), temperature ($T_P$) and flow rate ($F_{LR}$) sensor threshold values of the oil pipeline. If the readings are in the given threshold range, the data is sent to gateway (Gt(w) and IoT cloud (IoT(C)). If any abnormal issues found the alert send to Safety operation controller ($SOC_A$), drone yard ($UAV_A$) and activate both of them. Line 13-20 presents the detection section (DS) execution stages. Here vibration sensor ($V_b$), Acoustic sensor ($A_c$) and Methane gas sensor ($M_g$) are used to observe the third-party damages on the pipeline. Figure shown vibration graph which is logic-1 represents the vibration detection. Send data to MS using Zigbee transmitter ($D_{ZTX}$) and send to Safety operation controller ($SOC_A$), drone yard ($UAV_A$) and activate both of them for pipeline inspection. Line 22-30 give the operation of SOC. SOC Zigbee receiver ($SOC_{ZRX}$ =High) hooter is activated and alert the on field workers. Line 31-45 gives the operation of drone (UAV). After initializing the communication protocols and ESP 32 cam, GPS modules, UAV is activated ($UAV_{ZRX}$) after receiving signal from MS or DS. IR proximity sensor sense the pipeline which is embedded to drone to find the drone is on Line of Sight (LOS) or not (NLOS) on pipeline while inspection. The status is send to Gt(w)with RSSI value. Moreover the visuals from ESP 32 cam ($ESP_V$) and latitude and longitude from GPS ($G_{LL}$) are displayed in Esp32 web server. There user can find the leak if any and location of the leak. Line 46-50 show the after *Gt(w)* receiving the data packets from $M_{ZTX}$ *or* $D_{ZTX}$ display on *IoT (C) via ESP8266* Wi-Fi module.

```
Initialize _Serial Communication
Initialize _IoT sensors
Initialize _UAV
Initialize _SOC
Read MS ⟶ Sensor Val;
if (( P_R >1540 KN/m^2 & P_R <1600 KN/m^2 ) || (F_LR>10 L/m & F_LR <11 L/m)||(T_P >35^0 C & T_P <25^0 C)
    Send M_LTX → Gt(w) → IoT(C);
else
    Threshold_abnormal
    Send M_ZTX → SOC_A, UAV_A;
    Send M_LTX → Gt(w) → IoT(C);
end
Read DS ⟶ Sensor Val ;
if (V_b =1) and (A_c >40dB) then
    Check_ Third-party damages
    Send D_ZTX → SOC_A, UAV_A;
    Send D_ZTX → M_ZRX;
    if ( DS sensor> Range) then
        Read sensor → fault;
    end if
else
    Send D_ZTX → M_ZRX;
end
```

```
Upon reception of SOC_ZRX (M_ZTX || D_ZTX)
    if (SOC_ZRX = High)
        Act → Hooter;
    else
        SOC_ idle;
    end
end
Upon reception of UAV_ZRX (M_ZTX || D_ZTX)
    Initialize _Serial communication;
    Initialize _ESP 32, GPS;
    Activate _UAV → Leak identification;
    if (IR_s = 1) then
        UAVstatus → LOS;
        Send UAV_LTX → Gt(w) with RSSI;
        Send ESP_V, G_LL → Web server (192.168.43.48);
    else if (IR_s = 0 & T ≥ 20 sec) then
        UAVstatus → NLOS;
        Send UAV_LTX → Gt(w) with RSSI;
    else
        Comp_inspect;
    end
end
Upon reception of Gt(w) (M_ZTX || D_ZTX)
    Display_LCD;
    Active_ESP8266 wifi;
    Send ESP8266 → IoT (C);
end
```

### 6.3 Power Consumption Analysis

Power consumption analysis has been done for various IoT components and communication protocols used in this project as shown in figure 6.26. Here voltage measuring of IR sensor is shown. Table 6.5 gives the complete power analysis of IoT components used in this research work. Figure 6.27 presents the voltage, current, and power analysis using a graph.

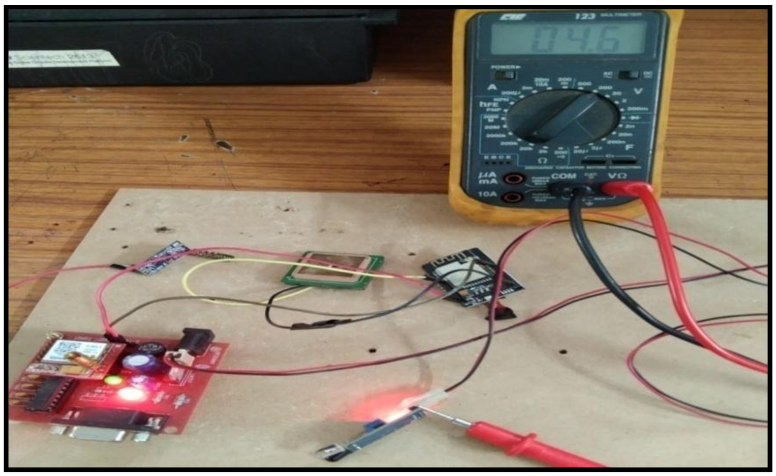



Figure 6.26 Measuring of voltage of IR proximity sensor

Table 6.5 Power consumption analysis

| Component | Voltage (V) | Current(mA) | Power (mW) |
|---|---|---|---|
| ATmega328P | 3.33 | 1.5 | 4.95 |
| Temperature Sensor | 3.2 | 3.2 | 10.24 |
| IR proximity Sensor | 4.6 | 33 | 151.8 |
| Humidity sensor | 3.5 | 2.5 | 7.5 |
| Pressure sensor | 4 | 8 | 32 |
| Flow meter | 7.5 | 16 | 120 |
| Vibration sensor | 3.3 | 15 | 49.5 |
| Acoustic sensor | 3 | 4.5 | 13.5 |
| Smoke detection sensor | 2.5 | 8 | 20 |
| XBee Transmitter | 3.3 | 42 | 138.6 |
| XBee Receiver | 3.3 | 35 | 115.5 |
| LoRa transmitter | 3.3 | 38.9 | 128.3 |
| LoRa receiver | 3.3 | 26.7 | 88.11 |

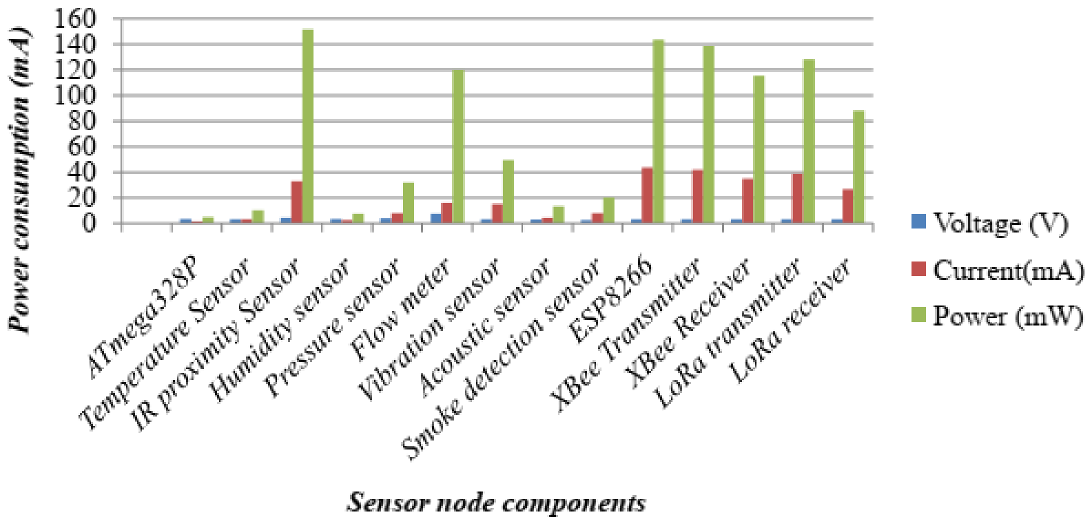



Figure 6.27 Power consumption analysis

## 6.4 Chapter Summary

This chapter summarizes the data received from the sensor nodes to the gateway are displayed in the Thingspeak IoT cloud and ESP32 web server for pipeline visuals collected by drone.. The acquired sensor values are analyzed in various cases for third-party damage and leak finding. Algorithm for oil pipeline monitoring and leak finding is addressed. Finally, the power consumption analysis for various IoT components used in this research is enhanced.

# CHAPTER-7

# CONCLUSION AND FUTURE SCOPE

The study of significant outcomes, as well as its novelty and future directions, is described in this chapter. Each objective's outcomes, as well as publications, are presented.

**7.1Conclusion**

It is essential to monitor oil pipelines to improve safety and minimize negative impact on people and the environment. The research aims to implement an oil pipeline monitoring system for the smooth transportation of oil through the pipeline using IoT technology. For achieving it, the research categorizes it into five objectives. The outcome of the five objectives is presenting here with features and publications.

**Objective-1: Deploying End Sensor Nodes on the Pipeline**

This objective is achieved by  deploying two end sensor nodes with customized hardware with ATMega 328p MCU, Zigbee and LoRa SX-1278 communication modules power up by solar energy with maximum rating of 12 Volts and 50 Watts solar panel interfaced with IoT sensors to monitor various parameters of the oil pipeline.  Here the 100 mts (Meters) of thermoplastic pipeline with 1.5inch outer and 0.5 inch inner diameter pipes is deployed and these thermoplastic pipes could be better alternative to steel for oil transportation as shown in figure.7.1. They are light weight and non-corrosive material with cost effective and easy installation.  Sensor nodes are deployed on the pipeline. The customized hardware prototype was assembled by designing the PCB layout and circuit. The simulation IoT various sensor interfacing with ATMega 328p in proteus software are observed before deployment of sensor node in real time.

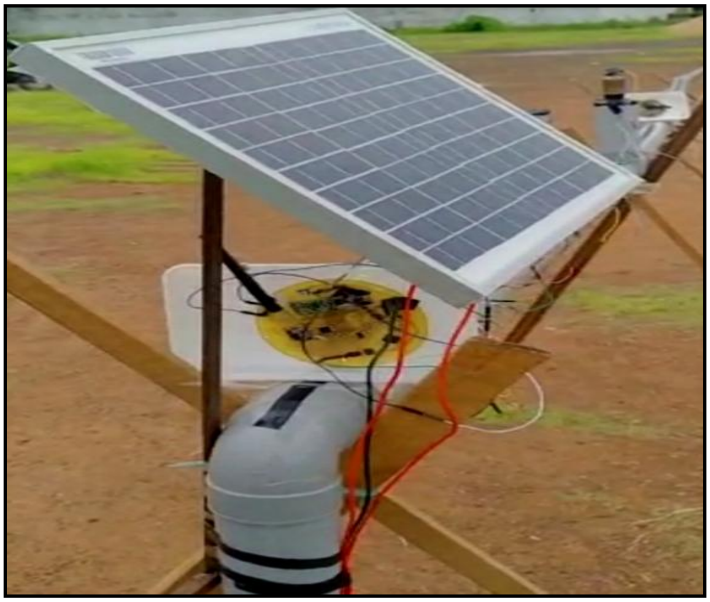


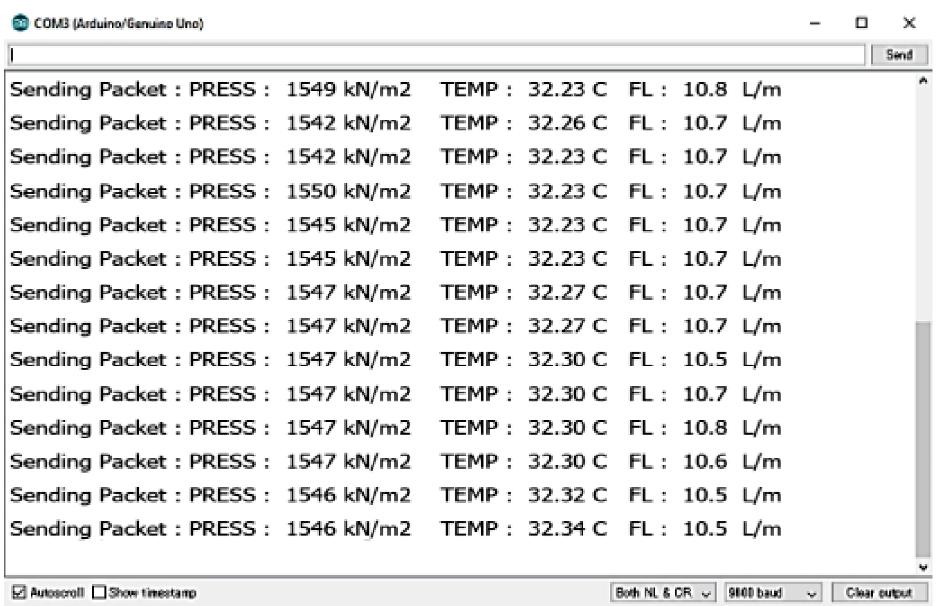
Figure 7.1 Sensor node with solar on the pipeline

**Objective.2: To Monitor Pipeline Parameters**

In this objective various pipeline parameters are measured for smooth oil transportation through the pipeline. Pipeline's numerous environmental conditions are monitored by the sensor nodes. Various parameters of the pipeline are like the temperature of the oil, pressure of the pipeline, flow check, vibrations, and acoustic waves are monitored using various IoT sensors and data communicated to gateway using LoRa SX-1278 communication protocol. Third-party damages and leaks of the pipeline are recognized using SW-420 vibration sensor and LM 393 acoustic sensor. The data acquired from sensor nodes is represented in chapter-6.Figure.7.2 represents the pipeline monitoring with various sensors.

Figure 7.2 Oil Pipeline monitoring

The sensor node data in figure 7.3 are illustrated from a serial monitor of Ardunio IDE and it displays temperature ($32^0$C), flow rate (10.7 L/m), and pressure (1549 $KN/m^2$) data of the pipeline. The strength of the LoRa signal is determined by sending and receiving sensor data from the transmitter (Tx) and receiver (Rx), as well as RSSI(-62dB) and SNR (9.25dB) metrics with the 2Km of range.



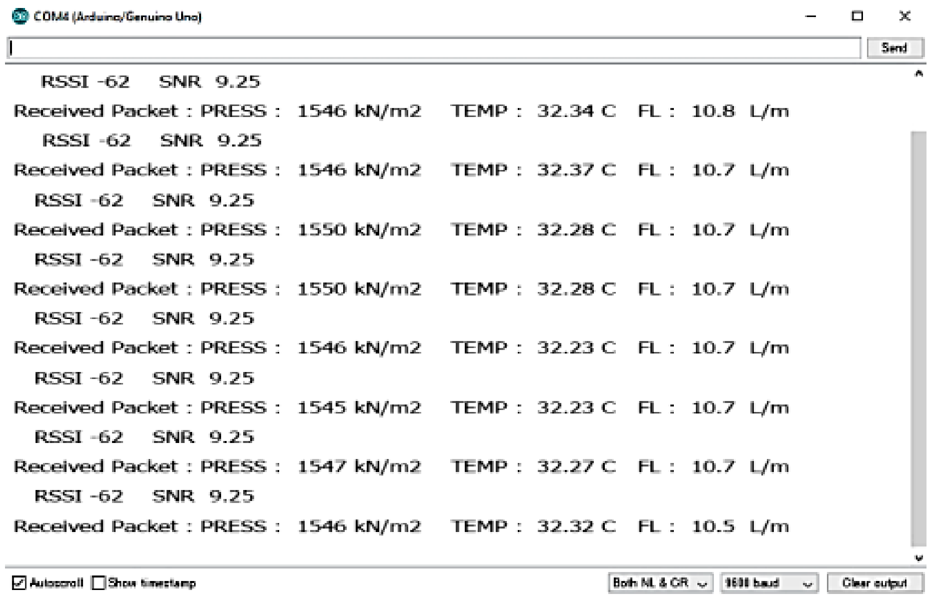



Figure 7.3 Serial communication of transmission and reception of sensor node

When abnormal issues are detected in the end sensor nodes, the safety operation controller (SOC) is activated to alert people nearby pipeline through Zigbee communication by activating the hooter. Figure.7.4 shows the hardware realization of the hooter with a customized board. ATMega 328 microcontrollers are interfaces with nRF24L01 2.4GHz RF module, HE JQC3FC relay, and hooter. The sensor node includes the voltage regulators LM7812 and LM7805 to handle the varied power supplies of 12 V and 5V.

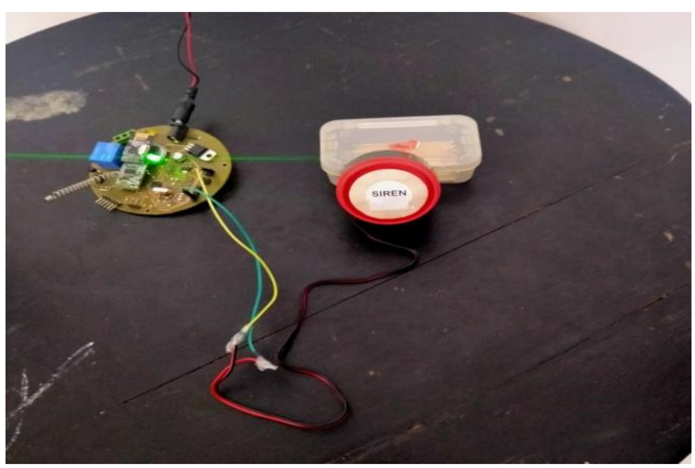



Figure 7.4 SOC with Hooter

**Objective 3: To Establish a Network between Sensor Nodes and LoRa Gateway**

This objective is achieved by establishing a LoRa network between the sensor node and the gateway. Various LoRa field parameters like Bandwidth, spreading factor, code rate, received signal strength indicator, receiver sensitivity, and SNR are calibrated during establishing communication using LoRa for extracting the interrelations between all the relevant parameters from a built LoRa network and gateway using OPNET simulation. Bandwidth (500 KHz), Spreading factor (SF-7) and code rate (4/5) are set as parameters in real time deployment of the network and achieved communication range up to 2km of distance. Moreover, using the same simulator Zigbee module was also tested in providing various parameters in 2.4GHz and 916MHz frequency bands in a simulation environment. Here parameters throughput, retransmission rate, PDR, and end-to-end delay, are compared from both frequency bands and set 2.4GHz band for deployment of the network. The simulations show that pipeline monitoring in relevant applications is more reliable, effective, and scalable. Finally, these communication protocol simulation results observed and set the parameters in a real-time testing environment.

**Objective-4 Design of Drone for On-demand Visual Data Collection**

This objective presents the necessity of drones in the oil industry and the design of the drone. This is achieved by the designing of a quadcopter drone using AutoCAD software. The design process of a quadcopter is carried out with configuration using AutoCAD software simulations for completing parameters displacement and stress of the bar, base plate, and quadcopter structure and assembled using various IoT components, microcontroller with the Zigbee, ESP32 Wi-Fi camera module, the global positioning system (GPS) module, the LoRa SX-1278 module, and the IR proximity sensors as discussed in chapter-5. The quad copter's with ABS plus plastic materials is designed with weight was at 727 G (grams) with enough lift it to a height up to 10 meters, as intended. The longest flight was 20 minutes achieved. Here Zigbee play important role in receiving an alert from the sensor node. Drone starts inspecting the pipeline as shown in figure.7.4. Here ESP 32 camera module interfaced with GPS collected the visuals of the damage and leak of the pipeline and communicated to the end user along with latitude and longitude data displayed in the ESP32 web server.

Figure 7.5 Drone inspecting pipeline

**Objective-5 Data Analysis and Forecasting With Internet of Things**

The objective is achieved by performing data analysis in various cases in pipeline monitoring and developed the gateway module with LCD and IoT cloud. Case-I gives the various parameter analysis for smooth transportation of oil through pipeline. Case-II presents the vibro-acoustic analysis for third-party damage occurs on the pipeline. Case-III gives the flow rate, pressure and vibro-acoustic analysis is carried out due to pipe leak. From above analysis, various parameters abnormal values are effectively noticed at pipeline damage and leak. Data communicated using gateway is embedded with LoRa and ESP8266 Wi-Fi module. It is employed to receive data from sensor nodes using Lora and transmit to IoT cloud server using esp8266 Wi-Fi module. The gateway with IoT cloud is shown in figure.7.6. The data from the pipeline monitoring section is shown on the LCD using the LoRa communication protocol. Furthermore, a graphical representation of data is represented in ThingSpeak IoT cloud as discussed in chapter-

6.Damage and leak point is localized using drone inspection of the pipeline and displayed the visuals in ESP32 web server.


Figure 7.6 Gateway with IoT cloud

**7.2 Novelty**

Hybrid architecture is developed to monitor all critical parameters of the pipeline using low complex system with long-range communication for smooth transportation of the oil through the pipeline.

**7.3Future Scope**

The current research effort has potential that can be expanded in future work to offer effective and efficient oil pipeline management solutions. The following are the results of the present research's future work. Energy harvesting from different sources poses a problem for researchers. It will need the creation of advanced power system procedures. It is feasible to remove energy storage systems like as batteries, super capacitors, and other devices used to power sensor nodes using a generic harvester**.** In remote regions, more infrastructure such as energy sources, battery backup, and sensors are placed to monitor pipeline conditions. As a result, there is a risk that this infrastructure may be stolen, thus it is critical to use modern technology to address these concerns.

## 7.4 PUBLICATIONS

### Patents

- Ch. Lakshmi Narayana, Rajesh Singh, Anita Gehlot, Lovi Raj Gupta, Patent titled "Method and device for Monitoring the Critical parameters of oil pipeline" granted on 16/2/2021, Patent number: 374608.
- Ch. Lakshmi Narayana, Rajesh Singh, Anita Gehlot, A PCT is filed and published with application no: WO2021100054A1 on27-05-2021.

### Journals

- Singh, Rajesh, Mohammed Baz, Ch Narayana, Mamoon Rashid, Anita Gehlot, Shaik Vaseem Akram, Sultan S. Alshamrani, Deepak Prashar, and Ahmed Saeed AlGhamdi. "*Zigbee and Long-Range Architecture Based Monitoring System for Oil Pipeline Monitoring with the Internet of Things*." Sustainability, vol. 13, no. 18 (2021): 10226.https://doi.org/10.3390/su131810226. [SCI with Impact Factor-3.251].

- Ch. Lakshmi Narayana, Rajesh Singh, Anita Gehlot, *Performance evaluation of LoRa based sensor node and gateway architecture for oil pipeline management* is published in "International Journal of Electrical & Computer Engineering", Vol. 12, no: 2,Feb-2022.[Scopus with SJR: 0.32].

### Conferences

- Ch. Lakshmi Narayana, Rajesh singh, Anita Gehlot, *Analysis of IoT sensors for Monitoring the Oil Pipeline Parameters* is published in International Conference on "Intelligent Circuits and Systems" ICICS 2020, June 2020.

- Ch. Lakshmi Narayana, Rajesh singh, Anita Gehlot, *Improvement of QOS by Optimizing 2.4 GHZ RF Network Parameters for Oil Pipeline Management* is published in International Conference on “Intelligent Communications and Control devices” ICICCD- 2020, Nov 2020.

- Ch. Lakshmi Narayana, Rajesh singh, Anita Gehlot, *Evaluation of Parameters of Wifi network for oil pipeline management using OPNET simulator* is published in International Conference on “Emerging trends and technologies on intelligent systems” ETTIS-2021, March -2021.

**Book Chapters**

- Ch. Lakshmi Narayana, Rajesh singh, Anita Gehlot, *Development of Solar Energy Harvesting Mechanism to Power up Sensor Node to Monitor the Parameters of Pipeline Using XBee Technology* published a book chapter in book titled: Energy Harvesting Technologies for Powering WPAN and IoT Devices for Industry 4.0 Up-Gradation. April-2020.

- Ch. Lakshmi Narayana, Rajesh singh, Anita Gehlot, *Analysis and Design of Oil Pipeline Leaks Monitoring System Using LoRa and IoT Network* published a book chapter in book titled:LoRA and IoT networks for Applications in Industry 4.0. April-2020.

## Bibliography

[1] M. Y. Aalsalem, W. Z. Khan, W. Gharibi, M. K. Khan, and Q. Arshad, "Wireless Sensor Networks in oil and gas industry: Recent advances, taxonomy, requirements, and open challenges", *Journal of Network and Computer Applications*, vol.113. Academic Press, pp. 87–97, 2018, doi: 10.1016/j.jnca..04.004.

[2] Oil industry overview [Online] http://petroleum.nic.in.

[3] K. Rehman and F. Nawaz, "Remote pipeline monitoring using wireless sensor networks", *International Conference on Communication, Computing and Digital Systems (C-CODE)*, pp. 32–37, 2017.

[4] L. Boaz, S. Kaijage, and R. Sinde, "An overview of pipeline leak detection and location systems", in *Proceedings of the 2nd Pan African International Conference on Science, Computing and Telecommunications (PACT 2014)*, pp. 133–137, 2014.

[5] Q. Xiao, J. Li, J. Sun, H. Feng, and S. Jin, "Natural-gas pipeline leak location using variation mode decomposition analysis and cross-time–frequency spectrum", *Measurement*, vol. 124, pp. 163–172, 2018.

[6] R. Cramer, D. Shaw, R. Tulalian, P. Angelo, and M. van Stuijvenberg, "Detecting and correcting pipeline leaks before they become a big problem", *Mar. Technol. Soc. J.*, vol. 49, no. 1, pp. 31–46, 2015.

[7] Z. Jia, Z. Wang, W. Sun, and Z. Li, "Pipeline leakage localization based on distributed FBG hoop strain measurements and support vector machine", *Optik (Stuttg)*, vol. 176, pp. 1–13, 2019.

[8] H. Attia and S. Balhassan, "Design of computerized monitoring and processing system for magnetic field controlling against the phenomenon of black powder in crude oil pipelines", *Int. J. Electr. Comput. Eng*, vol. 10, no. 5, p. 4639, 2020.

[9] Pipeline Incident 20 Year Trends PHMSA.' [Online]. Available: https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-20-year-trends.

[10] L. Dai, D. Wang, T. Wang, Q. Feng, and X. Yang, "Analysis and comparison of long-distance pipeline failures", *J. Pet. Eng*, 2017.

[11] J. Zhang, "Designing a cost-effective and reliable pipeline leak-detection system", *Pipes pipelines* Int., vol. 42, no. 1, pp. 20–26, 1997.

[12] Jang, D.; Park, H.; Choi, G. "Estimation of Leakage Ratio Using Principal Component Analysis and Artificial Neural Network in Water Distribution Systems". *Sustainability,* 2018.

[13] G. Geiger, D. Vogt, and R. Tetzner, "State-of-the-art in leak detection and localization", *Oil Gas Eur. Mag*, vol. 32, no. 4, p.193, 2006.

[14] Yazdekhasti, K. R. Piratla, S. Atamturktur, and A. A. Khan, "Novel vibration-based technique for detecting water pipeline leakage", *Struct. Infrastruct*. Eng, vol. 13, no. 6, pp. 731–742, 2017.

[15] A. Martini, M. Troncossi, and A. Rivola, "Leak detection in water-filled small-diameter polyethylene pipes by means of acoustic emission measurements", *Appl. Sci*, vol. 7, no. 1, p. 2, 2017.

[16] L. P. Peters, J. J. Daniels, and J. D. Young, "Ground penetrating radar as a subsurface environmental sensing tool", *Proc. IEEE*, vol. 82, no. 12, pp. 1802–1822, 1994.

[17] K. G. Aljuaid, M. A. Albuoderman, E. A. AlAhmadi, and J. Iqbal, "Comparative Review of Pipelines Monitoring and Leakage Detection Techniques", *International Conference on Computer and Information Sciences (ICCIS)*, pp. 1–6, 2020.

[18] A. Shukla and H. Karki, "Application of robotics in onshore oil and gas industry: A review" *Rob. Auton. Syst*, vol. 75, pp. 490–507, 2016.

[19] N. F. Henry and O. N. Henry, "Wireless sensor networks based pipeline vandalisation and oil spillage monitoring and detection: main benefits for nigeria oil and gas sectors", *SIJ Trans. Comput. Sci. Eng*. its Appl., vol. 3, no. 1, pp. 1–6, 2015.

[20] C M. A. Adegboye, W.-K. Fung, and A. Karnik, “Recent advances in pipeline monitoring and oil leakage detection technologies: Principles and approaches”, *Sensors,* vol. 19, no. 11, p. 2548, 2019.

[21] G. Allibert, M.-D. Hua, S. Krupínski, and T. Hamel, “Pipeline following by visual serving for Autonomous Underwater Vehicles”, *Control Eng. Pract,* vol. 82, pp: 151–160, 2019.

[22] C. Gómez and D. R. Green, “Small unmanned airborne systems to support oil and gas pipeline monitoring and mapping”, *Arab. J. Geosci*, vol. 10, no. 9, p. 202, 2017.

[23] S. Ali et al., “SimpliMote: A wireless sensor network monitoring platform for oil and gas pipelines”, *IEEE Syst. J*, vol. 12, no. 1, pp. 778–789, 2016.

[24] E. B. Priyanka, K. Krishnamurthy, and C. Maheswari, “Remote monitoring and control of pressure and flow in oil pipelines transport system using PLC based controller”, *International Conference on Green Engineering and Technologies (IC-GET)* , pp. 1–6, 2016.

[25] S. Razvarz, C. Vargas-Jarillo, R. Jafari, and A. Gegov, “Flow control of fluid in pipelines using PID controller*”, IEEE Access*, vol. 7, pp. 25673–256.2020

[26] L. O. Aghenta and M. T. Iqbal, “Low-cost, open source IoT-based SCADA system design using thinger IO and ESP32thing”, *Electronics*, vol. 8, no. 8, p. 822, 2019.

[27] C. WANG, M. LIU, A. XU, and J. ZHANG, “The application of PLC control system in oil and gas pipeline transportation”,*DEStech Trans. Eng. Technol*, 2017.

[28] E. B. Priyanka, C. Maheswari, M. Ponnibala, and S. Thangavel, “SCADA based remote monitoring and control of pressure & flow in fluid transport system using IMC-PID controller”, *Adv. Syst. Sci. Appl*, vol. 19, no. 3, pp. 140–162, 2019.

[29] A. Bröring *et al.*, “New generation sensor web enablement,” *Sensors,* vol. 11, no. 3, pp. 2652–2699, 2011.

[30] F. Nack, “An overview on wireless sensor networks technology and evolution,” *Sensors*, vol. 9, no. 9, pp. 6869–96, 2009.

[31] M. F. Othman and K. Shazali, “Wireless Sensor Network Applications: A Study in Environment Monitoring System”, *Procedia Eng.*, vol. 41, pp. 1204–1210, 2012.

[32] S. Savazzi, S. Guardiano, and U. Spagnolini, “Wireless sensor network modeling and deployment challenges in oil and gas refinery plants”, *Int. J. Distrib. Sens. networks*, vol. 9, no. 3, p. 383168, 2013.

[33] J. Sun, Z. Zhang, and X. Sun, “The Intelligent Crude Oil Anti-theft System Based on IoT under Different Scenarios”, *Procedia Comput. Sci*, vol. 96, pp. 1581–1588, 2016, doi: 10.1016/j.procs.2016.

[34] K. Kamalampet, D. Vyas, S. Sahu, and S. Shah, “A wireless sensor network based pipeline monitoring system”, “*International Conference on Signal Processing and Integrated Networks (SPIN)*, pp. 412–419, 2014.

[35] S. Ali, S. Bin Qaisar, H. Saeed, M. F. Khan, M. Naeem, and A. Anpalagan, “Network challenges for cyber physical systems with tiny wireless devices: A case study on reliable pipeline condition monitoring”, *Sensors*, vol. 15, no. 4, pp. 7172–7205, 2015..

[36] Y. Song, J. Lin, M. Tang, and S. Dong, “An Internet of Energy Things Based on Wireless LPWAN,” *Engineering*, vol. 3, pp. 460–466, 2017.

[37] Howitt and J. A. Gutierrez, “IEEE 802.15. 4 low rate-wireless personal area network coexistence issues”, “IEEE Wireless Communications and Networking”, vol. 3, pp. 1481–1486, 2003

[38] D. Stevanovic and N. Vlajic, “Performance of IEEE 802.15. 4 in wireless sensor networks with a mobile sink implementing various mobility strategies”, *IEEE Conference on Local Computer Networks (LCN)*, pp. 680–688, 2008.

[39] SJ. Baviskar, A. Mulla, M. Upadhye, J. Desai, and A. Bhovad, “Performance analysis of ZigBee based real time Home Automation system”, *International*

*Conference on Communication, Information & Computing Technology (ICCICT)*, pp. 1–6, 2015.

[40] J.-S. Lee and Y.-C. Huang, “ITRI ZBnode: A ZigBee/IEEE 802.15. 4 platform for wireless sensor networks”, *IEEE International Conference on Systems, Man and Cybernetics*, vol. 2, pp. 1462–1467, 2006.

[41] M. A. Moridi, Y. Kawamura, M. Sharifzadeh, E. K. Chanda, M. Wagner, and H. Okawa, “Performance analysis of ZigBee network topologies for underground space monitoring and communication systems”, *Tunn. Undergr. Sp. Technol.*, vol. 71, pp. 201–209, 2018.

[42] P. P. Ray, “A survey of IoT cloud platforms”, *Futur. Comput. Informatics J*, vol. 1, no. 1–2, pp. 35–46, Dec. 2016. doi:10.1016/j.fcij.2017.02.001.

[43] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, “Internet of things for smart cities”, *IEEE Internet Things J*, vol. 1, no. 1, pp. 22–32, 2014, doi: 10.1109/JIOT.2014.2306328.

[44] E. B. Priyanka, C. Maheswari, and B. Meenakshipriya, “Parameter monitoring and control during petrol transportation using PLC based PID controller”, *J. Appl. Res. Technol*, vol. 14, no. 2, pp. 125–131, 2016.

[45] S. G. Varghese, C. P. Kurian, V. I. George, A. John, V. Nayak, and A. Upadhyay, ‚Comparative study of ZigBee topologies for IoT-based lighting automation,‘ IET Wirel. Sens. Syst., vol. 9, no. 4, pp. 201–207, 2019.

[46] Hognogi, G.-G.; Pop, A.-M.; Marian-Potra, A.-C.; Someșfălean, T. “The Role of UAS—GIS in Digital Era Governance. A Systematic Literature Review”. *Sustainability*. 2021.

[47] El Himer, S. El Ayane, S.; El Yahyaoui, S.; Salvestrini, J.P.; Ahaitouf, A. “Photovoltaic Concentration: Research and Development”. *Energies,* **2020.**

[48] N. Mohamed, J. Al-Jaroodi, I. Jawhar, and S. LazarovaMolnar, “A service-oriented middleware for building collaborative UAVs,” *Journal of Intelligent & Robotic Systems,* vol. 74, no. 1-2, pp. 309–321, 2014.

[49] F. Mohammed, I. Ahmed, N. Mohamed, J. Al-Jaroodi, and I. Jawhar, “Opportunities and challenges of using UAVs for Dubai Smart city,” *International Conference on New Technologies, Mobility and Security (NTMS)*, pp. 1–4, April 2014.

[50] Murvai PS, Silea I, “A survey on gas leak detection and localization techniques”. *J Loss Prev Proc Ind* 25:966–973.2012.

[51] R.Morais,S.G.Matos,M.A.Fernandes,A.L.Valente,S.F.Soares,P.Ferreira, andReis. “Sun,windandwaterflow asenergysupplyforsmallstationarydataacquisitionplatforms”,*Comput.Electron.Agricult*.120–132, 2008.

[52] P. T. V. Bhuvaneswari, R. Balakumar, V. Vaidehi, and P. Balamuralidhar. “Solar energy harvesting for wirelesssensor networks”.*InternationalConferenceonComputationalIntelligence,CommunicationSystemsand Networks (CICSYN*), *IEEE*,57–61, 2009.

[53] Ibrahim, Rosdiazli & Chung, Tran & Hassan, Sabo & Bingi, Kishore & Salahuddin, Siti, “Solar Energy Harvester for Industrial Wireless Sensor Nodes”. *Procedia Computer Science*. 2012.

[54] Z. Zhou, J. Gong, A. Roda, and K. Farrag, “Multiresolution change analysis framework for postdisaster assessment of natural gas pipeline risk”, *Transportation Research Record*, vol. 2595, pp. 29–39, 2016.

[55] K. Boonjun, N. Keeratipranon, and N. Chinpanthana, ‘‘Real time automatic object detection by using template matching for protecting pipelines”,*Int. Workshop Adv. Image Technol*.2018.

[56] The World factbook. Alaska. [Onlinw] Avaliable: http://www.bp.com/en_us/bp-us/what-we-do/technology/drones-take-flight-alaska.html.

[57] FAA opens the Arctic to commercial small unmanned aircraft. [Online] http://www.faa.gov/news/updates/?newsId=73981&omniRss=news_ updates Aoc& cid= 101_ N_ U.

[58] Pipeline monitoring, oil & gas security. 2015 [Online]: http://www. aeronautics-sys.com/home-page/solutions/hls/.

[59] Zhang, S., Wang, X., Cheng, Y.F. *et al.* "Modeling and analysis of a catastrophic oil spill and vapor cloud explosion in a confined space upon oil pipeline leaking". *Pet. Sci.* 17, 556–566 .2020.

[60] Wanasinghe, Thumeera & Gosine, Ray & De Silva, Oscar & Mann, G.K.I. & James, Lesley & Warrian, Peter. "Unmanned Aerial Systems for the Oil and Gas Industry: Overview, Applications and Challenges". *Sensors*. 2020.

[61] A. Correlj´ e and C. van der Linde, "Energy supply security and geopolitics: A European perspective," *Energy Policy***,** vol. 34, no. 5, pp. 532–543, 2006.

[62] W. Z. Khan, M. Y. Aalsalem, W. Gharibi, and Q. Arshad, "Oil and gas monitoring using wireless sensor networks: requirements, issues and challenges," *International Conference on Radar, Antenna, Microwave,Electronics, and Telecommunications, ICRAMET***,** pp. 31–35,October 2016.

[63] P. K. Dey, "Analytic hierarchy process analyzes risk of operating cross-country petroleum pipelines in india," *Natural Hazards Review***,** vol. 4, no. 4, pp. 213–221, 2003.

[64] P. K. Dey, "Managing project risk using combined analytic hierarchy process and risk map," *Applied Soft Computing***,** vol.10, no. 4, pp. 990–1000, 2010.

[65] S. Karimi, R. Sam, J. Balist, and S. M. Bigdeli, "Pipeline risk assessment by using hazard risk assessment, (HAZOP) Method (Case study: Gas transmission Pipeline Of Savadkooh, Iran)," Environmental Science: An Indian Journal**,** vol. 12, no. 3, 2016.

[66] M. Bai, Y. Du, Y. Chen, Y. Xing, and P. Zhao, "Risk assessment of long gas and oil pipeline projects inducing landslide disasters during construction," *Journal of Performance of Constructed Facilities***,** vol. 31, no. 5, 2017.

[67] J. Soszynska, “Reliability and risk evaluation of a port oil pipeline transportation system in variable operation conditions,” *International Journal of Pressure Vessels and Piping***,** vol. 87, no. 2-3, pp. 81–87, 2010.

[68] Z. Y. Han and W. G. Weng, “Comparison study on qualitative and quantitative risk assessment methods for urban natural gas pipeline network,” *Journal of Hazardous Materials***,** vol. 189, no. 1-2, pp. 509–518, 2011.

[69] A. Jamshidi, A. Yazdani-Chamzini, S. H. Yakhchali, and S. Khaleghi, “Developing a new fuzzy inference system for pipeline risk assessment,” *Journal of Loss Prevention in the Process Industries***,** vol. 26, no. 1, pp. 197–208, 2013.

[70] PHMSA [online] Available:http://primis.phmsa.dot.gov/comm/reports/safety/PSI.html. 2015.

[71] Nikles, M., et al, “Leakage detection using fiber optics distributed temperature monitoring in Smart Structures and Materials*”, International Society for Optics and Photonics*.2004.

[72] Qiang Fu , HongJie Wan, Fupeng Qiu, “Pipeline Leak Detection based on Fiber Optic Early- Warning System”, *Procedia Engineering* , 2010.

[73] Fish, H.D. and K.H. Kalberer, “Method And Apparatus For Pipeline Inspection”., US Patent 3,885,091. 1975.

[74] Peters, L.; Daniels, J.J.; Young, J.D. “Ground penetrating radar as a subsurface environmental sensing tool”, *Proc. IEEE* , 1994.

[75] E.W. McAllister, Pipeline Drying, *Pipeline Rules of Thumb Handbook*, Gulf Professional Publishing, 2005, Pages 163-175, ISBN 9780750678520.

[76] Adedeji, K.B.; Hamam, Y.; Abe, B.T.; Abu-Mahfouz, A.M, “Towards achieving a reliable leakage detection and localization algorithm for application in water piping networks: overview”, *IEEE Access*,2017.

[77] Manekiya, M.H.; Arulmozhivarman, P. “Leakage detection and estimation using IR thermography”. “*International Conference on Communicat and Signal Processing (ICCSP)*, pp. 1516–1519, 2016.

[78] Wan, J., et al, “Hierarchical leak detection and localization method in natural gas pipeline monitoring sensor networks”. *Sensors*, p.189-214, 2011.

[79] Martini, A.; Rivola, A.; Troncossi, M, “Autocorrelation Analysis of Vibro-Acoustic Signals Measured in a Test Field for Water Leak Detection”, *Appl. Sci*. 2018.

[80] Indrayani, et.al; Measurement and Evaluation of Sound Intensity at The Medan Railway Station Using a Sound Level Meter. Journal of Physics: Conference Series. 1428. 012063. 10.1088/1742-6596/1428/1/012063.2020.

[81] Yazdekhasti, S.; Piratla, K.R.; Atamturktur, S.; Khan, A “Novel vibration-based technique for detection of water pipeline leakage”. *Struct. Infrastruct. Eng*. 2017.

[82] El-Zahab, S.; Mohammed Abdelkader, E.; Zayed, T. “An accelerometer-based leak detection system”. *Mech. Syst.Signal Process*, 2018.

[83] Xu, M. et.al;. Determination of natural frequencies of fluid-conveying pipes using homotopy perturbation method. Computers & Mathematics with Applications. 60. 520-527. 10.1016/j.camwa.2010.

[84] R. S. Whaley Reet, J.V., Nicholas, R.E., “A tutorial on computer based leak detection methods,” *Tech. Rep.*, 1992.

[85] Bin Md Akib, A., N. bin Saad, and V. Asirvadam. “Pressure point analysis for early detection system in Signal Processing and its Applications*”, IEEE International Colloquium on. 2011*.

[86] Arifin, B.; Li, Z.; Shah, S.L.; Meyer, G.A.; Colin, A. “A novel data-driven leak detection and localization algorithm using the Kantorovich distance”, *Comput. Chem.Eng*. 2018.

[87] Murvay, P.; Silea, I, “A survey on gas leak detection and localization techniques”. *J. Loss Prev. Process Ind*, 25, 966– 973, 2012.

.

[88] Wang, L.; Narasimman, S.C.; Ravula, S.R.; Ukil A, "Water ingress detection in low- pressure gas pipelines using distributed temperature sensing system*"*. *IEEE Sens. J*, 17, 3165–3173, 2017.

[89] A. Kayode Coker, CHAPTER 3 - Fluid Flow, Fortran Programs for Chemical ProcessDesign, Analysis, and Simulation, Gulf Professional Publishing, 1995, Pages 150-255,ISBN 9780884152804.

[90] Boaz, L.; Kaijage, S.; Sinde, R. "An overview of pipeline leak detection and location systems". *International Conference on Science, Computing and Telecommunications (PACT)* 2014.

[91] Santos, et.al;. Factors That Affect Crude Oil Viscosity And Techniques To Reduce It: *A Review. Brazilian Journal of Petroleum and Gas*. 2017.

[92] Sang, Y.; Zhang, J.; Lu, X.; Fan, Y. "Signal processing based on wavelet transform in pipeline leakage detection and location". International Conference on Intelligent Systems Design and Applications, pp. 734–739,2006.

[93] Akyildiz, I.F.; Su, W.; Sankarasubramaniam, Y.; Cayirci, E. "Wireless Sensor Networks: A Survey", *Comput.Netw, 38*, 399–422,2002.

[94] Kandris, D.; Nakas, C.; Vomvas, D.; Koulouras, G. "Applications of Wireless Sensor Networks: An Up-to-Date Survey". *Appl. Syst. Innov,* 2020.

[95] Arampatzis, T.; Lygeros, J.; Manesis, S. "A Survey of Applications of Wireless Sensors and Wireless Sensor Networks*". IEEE International Symposium on, Mediterrean Conference on Control and Automation Intelligent Control*, p. 719, 2005.

[96] Xie, M.; Han, S.; Tian, B.; Parvin, S. "Anomaly detection in wireless sensor networks: A survey". *J. Netw.Comput. Appl.* 2011.

[97] Myllyla, R, "Vital Sign Monitoring System with Life Emergency Event Detection using Wireless Sensor Network". *IEEE Conference on Sensors,* pp. 518–521, 2006.

[98] You, Z.; Mills-Beale, J.; Pereles, B.D.; Ong, K.G. "A Wireless, Passive Embedded Sensor for Real-Time Monitoring of Water Content in Civil Engineering Materials". *IEEE Sens. J.* 2008.

[99] Hao, Q.; Brady, D.J.; Guenther, B.D.; Burchett, J.B.; Shankar, M.; Feller, S. "Human tracking with wireless distributed pyroelectric sensors". *IEEE Sens. J.* 2006.

[100] Sundmaeker, H.; Guillemin, P.; Friess, P.; Woelfflé, S. "Vision and Challenges for Realising the Internet of Things", *European Commission: Brussels, Belgium*, 2010.

[101] Zaslavsky, A.; Perera, C.; Georgakopoulos, D, "Sensing as a Service and Big Data. *International Conference on Advances in Cloud Computing (ACC)*, 26–28 July 2012.

[102] Atzori, L.; Iera, A.; Morabito, G. "The internet of things: A survey". Comput. Netw. 2010.

[103] Middleton, P.; Kjeldsen, P.; Tully, J. Forecast, "The Internet of Things, Worldwide, 2013.

[104] Perera, C.; Zaslavsky, A.; Christen, P.; Georgakopoulos, D, "Sensing as a service model for smart cities supported by internet of things". *Trans. Emerg. Telecommun. Technol*. 2014.

[105] Chen, H.; Chiang, R.H.L.; Storey, V.C. "Business Intelligence and Analytics: From Big Data to Big Impact", *MIS Q*, 2012.

[106] Ashton, K. "internet of things" *thing. RFiD J*. 2009.

[107] Gil, D.; Ferrández, A.; Mora-Mora, H.; Peral, J. "Internet of Things: A Review of Surveys Based on Context Aware Intelligent Services". *Sensors*, 2016.

[108] Li, S.; Xu-Da, L.; Zhao, S. "The internet of things: A survey". *Inf. Syst,17*, 243–259. *Front.* 2015.

[109] F. Samie, L. Bauer and J. Henkel. "IoT technologies for embedded computing: A survey". *International Conference on Hardware/Software Codesign and System Synthesis (CODES+ISSS)*, pp. 1-10, 2016.

[110] Affairs, M. of E. n.d. “Internet of Things in the Netherlands Applications trends and potential impact on radio spectrum”.*Startix*.2015.

[111] Frantz, T. L. & Carley, K. M. “A formal characterization of cellular networks”. Available at SSRN 2726808, 2005

[112] Alliance, L. “A technical overview of LoRa and LoRaWAN. Area Network Technology”. *In Proceedings of EWC*. pp.119-124. 2016.

[113] Mekki, Kais and Eddy Bajic. “A comparative study of LPWAN technologies for large-scale IoT deployment”. *ICT Express*. 2018.

[114] Y.-.E. Wang et al. “A Primer on 3GPP Narrowband Internet of Things”. *IEEE Communications Magazine*.vol. 55, no. 3, pp. 117-123. 2017

[115] LoRa [Online] Avaliable: https://lora-alliance.org/about-lorawan.

[116] Seller, O.B.; Sornin, N. “Low Power Long Range Transmitter”. *US Patent* 9,252,834, 2 February 2016.

[117] Mikhaylov, K.; Petäjäjärvi, J.; Hänninen, T. “Analysis of the Capacity and Scalability of the LoRa Wide Area Network Technology”. Wireless Conference. pp. 1–6. 2016.

[118] Centenaro, M.; Vangelista, L.; Zanella, A.; Zorzi, M. “Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios”. *ArXiv* 2015.

[119] Neumann, P.; Montavond, J.; Noel, T. “Indoor Deployment of Low-Power Wide Area Networks (LPWAN): A LoRaWAN Case Study”. *International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob),* 17–19 , 2016.

[120] Petäjäjärvi, J.; Mikhaylov, K.; Hämäläinen, M.; Iinatti, J. “Evaluation of LoRa LPWAN Technology for Remote Health and Wellbeing Monitoring”. *International Symposium on Medical Information and Communication Technology (ISMICT),* March 2016.

[121] Petajajarvi, J.; Mikhaylov, K.; Roivainen, A.; Hanninen, T.; Pettissalo, M. “On the Coverage of LPWANs: Range Evaluation and Channel Attenuation Model

for LoRa Technology". *International Conference on ITS Telecommunications (ITST).* 2015.

[122] Adhikary, Ansuman et al. "Performance Evaluation of NB-IoT Coverage". *IEEE Vehicular Technology Conference (VTC-Fall)*. 2016.

[123] Son, S.; Park, Y.; Park, Y. A Secure, Lightweight, and Anonymous User Authentication Protocol for IoT Environments. *Sustainability* **2021**.

[124] López P, Fernández, D, Jara A. J, & Skarmeta A. F. "Survey of Internet of Things Technologies for Clinical Environments". *27th International Conference on Advanced Information Networking and Applications Workshops*. pp. 1349-1354. 2013.

[125] Estrin, D., Girod, L., Pottie, G. and Srivastava, M. "Acoustics, Speech, and Signal Processing", *IEEE International Conference on Instrumenting the World with Wireless Sensor Networks,* 4, P 2033-2036.2001.

[126] Yang, C.T., Chen, S.T., Chang, C.H., Den, W. and Wu, C.C. "Implementation of an Environmental Quality and Harmful Gases Monitoring System in Cloud". *Journal of Medical and Biological Engineering*, 1-14.2018.

[127] Zigbee Alliance: [Online]. Available: https://www.zigbee.org. Accessed 03 Feb 2020.

[128] Vangelista, L., Zanella, A., Zorzi, M. "Long-range IoT technologies: the dawn of LoRa". *Future Access Enablers for Ubiquitous and Intelligent Infrastructures*, vol. 159, pp. 51–58. Springer, 2015.

[129] Porkodi R & Bhuvaneswari V. "The Internet of Things (IoT) applications and communication enabling technology standards": An overview. *International Conference on of Intelligent Computing Applications (ICICA)*. 2014.

[130] Rahman A. "Comparison of Internet of Things ( IoT ) Data Link Protocols". *Networking and communication* 2015.

[131] Stefan Mangold, Sunghyun Choi, Peter May, Ole Klein1, Guido Hiertz1, Lothar Stibor, "IEEE 802.11e Wireless LAN for Quality of Service"2002.

[132] Dawotola, Alex W., P. H. A. J. M. Van Gelder, and J. K. Vrijling. "Decision analysis framework for risk management of crude oil pipeline system." *Advances in Decision Sciences*, 2011.

[133] RezaAkhondi, Mohammad, et al. "Applications of wireless sensor networks in the oil, gas and resources industries." *2010 24th IEEE International Conference on Advanced Information Networking and Applications*. IEEE, 2010.

[134] Lee, Lam Hong, et al. "Oil and gas pipeline failure prediction system using long range ultrasonic transducers and Euclidean-Support Vector Machines classification approach." *Expert Systems with Applications* “2013.

[135] Wan, Jiangwen, et al. "Hierarchical leak detection and localization method in natural gas pipeline monitoring sensor networks." *Sensors* 189-214.2012.

[136] Zhang, Yu, et al. "Leak detection monitoring system of long distance oil pipeline based on dynamic pressure transmitter." *Measurement* .382-389.2014.

[137] Owojaiye, Gbenga, and Yichuang Sun. "Focal design issues affecting the deployment of wireless sensor networks for pipeline monitoring." *Ad Hoc Networks*.1237-1253.2014.

[138] Ossai, Chinedu I. "Advances in asset management techniques: An overview of corrosion mechanisms and mitigation strategies for oil and gas pipelines." *ISRN Corrosion.* 2012.

[139] Adejo, Achonu O., et al. "Oil and gas process monitoring through wireless sensor networks: A survey." *Ozean Journal of Applied Science* .2013.

[140] Anatoliy, Bazhenov, et al. "Main pipelines corrosion monitoring device." *IOP Series: Earth and Environmental Science*. Vol. 50. No. 1. IOP Publishing, 2018.

[141] Tan, M., et al. "An Overview of Recent Progresses in Acquiring, Visualizing and Interpreting Pipeline Corrosion Monitoring Data." *CORROSION 2018. NACE International*, 2018.

[142] Zhou Z, et.al; Multiresolution Change Analysis Framework for Postdisaster Assessment of Natural Gas Pipeline Risk. Transportation Research Record. 2016;2595(1):29-39. doi:10.3141/2595-04 .

[143] Hognogi, G.-G.; Pop, A.-M.; Marian-Potra, A.-C.; Someșfălean, T. The Role of UAS–GIS in Digital Era Governance. A Systematic Literature Review. *Sustainability* 2021, *13*, 11097. https://doi.org/10.3390/su131911097.

[144] Xu, Yunze, et al. "Experimental study on pipeline internal corrosion based on a new kind of electrical resistance sensor." *Sensors and Actuators B: Chemical*, 37-47. 2016.

[145] Song, Huajun, et al. "An infrared non-contact framework for monitoring the liquid levels in natural gas pipelines." *International Journal of Oil, Gas and Coal Technology*,317-327,2017.

[146] Gautam, Abhinav, et al. "Optical sensing and monitoring architecture for pipelines using optical heterodyning and FBG filter." *Optik* , 9161-9166.2016.

[147] Rehman, Khawar, and Faiza Nawaz. "Remote pipeline monitoring using wireless sensor networks." *International Conference on Communication, Computing and Digital Systems (C-CODE)*. IEEE, 2017.

[148] Albaseer, Abdullatif, and UthmanBaroudi. "Node placement approaches for pipelines monitoring: simulation and experimental analysis." *International Journal of Sensor Networks*,147-158, 2017.

[149] Bhavyarani, M. P., UB MahadevaSwamy, and MB Shrynik Jain. "Inter Integrated WSN for Crude Oil Pipeline Monitoring". *International Journal of Computer Network and Information Security*, 2018.

[150] Babazadeh, Mehrdad. "Edge analytics for anomaly detection in water networks by an Arduino101-LoRa based WSN". *ISA transactions*, 2019.

[151] André C, et.al; Chapter 11 - Design and Construction of Offshore Pipelines, *Handbookof Offshore Engineering, Elsevier,Pages 891-937,ISBN 9780080443812,2005.*

[152] Najmi, Junaid et.al; Analysis Of Velocity Profile For Laminar Flow In A Round Pipe.*International Conference on Aerospace Science & Engineering (ICASE),* 2017.

[153] J. Sun, Z. Zhang and X. Sun, “The Intelligent Crude Oil Anti-theft System Based on IoT Under Different Scenarios,” *Procedia Computer Science*, pp.1581-1588, 2016.

[154] Ali, Salman, et al. "Network challenges for cyber physical systems with tiny wireless devices: A case study on reliable pipeline condition monitoring." *Sensors*, 7172-7205.2015.

[155] Gonzalo PajaresMartinsanz , “Sensors for Fluid Leak Detection”, *Sensors,2015*. doi:10.3390/s150203830.

[156] S. Savazzi, S. Guardiano and U. Spagnolini, “Wireless sensor network modeling and deployment challenges in oil and gas refinery plants”, *International Journal of Distributed Sensor Networks*, vol. 9, no. 4, pp. 383168, 2013.

[157] S. Savazzi, U. Spagnolini, L. Goratti, D. Molteni, M. Latva-aho and M.Nicoli, "Ultra-wide band sensor networks in oil and gas explorations," in *IEEE Communications Magazine*, vol. 51, no. 4, pp. 150-160, April 2013. doi: 10.1109/MCOM.2013.6495774.

[158] Lianshuang Dai,1,2 Dongpo Wang,1 Ting Wang,3 Qingshan Feng,2 and Xinqi Yang, “Analysis and Comparison of Long-Distance Pipeline Failures”,*Journal of Petroleum Engineering Volume*, 2018.

[159] Akinori tamura,Masahiro Miki,Naoyuki Kono,“A non-contact ultrasonic sensor for general corrosion inspection of thin lates”, *International Conference on Nuclear Engineering*,2018.

[160] Zhijin Qin, Frank Y. Li, Geoffrey Ye Li, Julie A. McCann, and Qiang Ni, “Low-Power Wide-Area Networks for Sustainable IoT”, *IEEE Access*, 2019.

[161] Gabriel M. Hoffmann, Haomiao Huang, Steven L. Waslander, Claire J. Tomlin, “Quadrotor Helicopter Flight Dynamics and Control: Theory and Experiment.” *American Institute of Aeronautics and Astronautics*.2007.

[162] L. Klauske, T. Lorenz, N. Colberg, M. Janke, U. M¨onich, N. Nothing, L. Thiele, F. Venzke, T. Wernicke S. Zeiler and R. Kusch, “DSP-Copter - A

Quadrotor Helicopter Controlled by a Digital Signal Processor," *ELITE-Project Report Summary*.

[163] Christian FinkPetersen, Henrik, Hansen, Steffen Larsson, Lars Bo Theilgaard Madsen, Michael Rimestad, "Autonomous Hovering with a Quadrotor Helicopter," *AALBORG University*, June 2, 2008.

[164] Kuantama, E., Craciun, D., Tarca, I., & Tarca, R. "Quadcopter Propeller Design and Performance Analysis". *In New Advances in Mechanisms, Mechanical Transmissions and Robotics .Springer International Publishing*.2017.

[165] Jerrin Bright, R Suryaprakash, S Akash and A Giridharan, "Optimization of quadcopter frame using generative design and comparison with DJI F450 drone frame", *International Conference on Robotics, Intelligent Automation and Control Technologies (RIACT 2020*) 2-3 October 2020.

[166] Vlah, Daria & Žavbi, Roman & Vukašinović, Nikola. "Evaluation Of Topology Optimization And Generative Design Tools As Support For Conceptual Design". *Proceedings of the Design Society*.2020.

[167] M D Stroia et al. "Case studies for automotive components using CAD and CAE Techniques 1426 012047. 2020

[168] Buonamici, Francesco & Carfagni, Monica & Furferi, Rocco & Volpe, Yary & Governi, Lapo. "Generative Design" *An Explorative Study*. 2020.

[169] Abdel Ilah Alshbatat, Ashar Khamaisa, Mais Khreisat, "daptive Control System for an Autonomous Quadrotor Unmanned Aerial Vehicle", *Procedia Computer Science,* 2009.

[170] Dey, Prasanta Kumar, Stephen O. Ogunlana, and SittichaiNaksuksakul. "Risk-based maintenance model for offshore oil and gas pipelines: a case study." *Journal of Quality in Maintenance Engineering,* 169-183.2004.

[171] Yuhua, Dong, and Yu Datao. "Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis." *Journal of loss prevention in the process industries* 18.2. 83-88.2005.

[172] Ho, Michael & El-Borgi, Sami & Patil, Devendra & Song, Gangbing. “Inspection and monitoring systems subsea pipelines: A review paper”, *Structural Health Monitoring*.2019.

[173] Mohamadi, Farrokh. "Vertical takeoff and landing (VTOL) small unmanned aerial system for monitoring oil and gas pipelines." *U.S. Patent* No. 8,880,241. 4 Nov. 2014.

[174] Breon, L. J., J. K. Van Velsor, and J. L. Rose. "Guided wave damage detection tomography for structural health monitoring in critical zones of pipelines." 2007.

[175] Tan, M., et al. "An Overview of Recent Progresses in Acquiring, Visualizing and Interpreting Pipeline Corrosion Monitoring Data." *CORROSION .Nace International*, 2018.

[176] Yu, Huaping, and Mei Guo. "An efficient oil and gas pipeline monitoring systems based on wireless sensor networks." *International Conference on Information Security and Intelligent Control. IEEE*, 2012.

[177] El-Darymli, Khalid, Faisal Khan, and Mohamed H. Ahmed."Reliability modeling of wireless sensor network for oil and gas pipelines monitoring." *Sensors & Transducers*, 2009.

[178] Jawhar, Imad, Nader Mohamed, and KhaledShuaib. "A framework for pipeline infrastructure monitoring using wireless sensor networks." *Wireless Telecommunications Symposium. IEEE*, 2007**.**

[179] Sinha, Sunil K., and Mahesh D. Pandey."Probabilistic neural network for reliability assessment of oil and gas pipelines." *Computer-Aided Civil and Infrastructure Engineering* 17.5.320-329.2002.

[180] Jawhar, Imad, et al. "A routing protocol and addressing scheme for oil, gas, and water pipeline monitoring using wireless sensor networks." *International Conference on Wireless and Optical Communications Networks (WOCN'08). IEEE*, 2008.

[181] Parvizsedghy, Laya, et al. "Condition-based maintenance decision support system for oil and gas pipelines." *Structure and Infrastructure Engineering* 1323-1337.2015.

[182] El-Abbasy, Mohammed S., et al. "Artificial neural network models for predicting condition of offshore oil and gas pipelines." *Automation in Construction* 50-65.2014.

[183] Kabir, Golam, RehanSadiq, and Solomon Tesfamariam."A fuzzy Bayesian belief network for safety assessment of oil and gas pipelines." *Structure and Infrastructure Engineering* .2016.

[184] Mahmoodian, M.; Qingi, C. Failure assessment and safe life prediction of corroded oil and gas pipelines. *J.Pet. Sci. Eng***.**2017, 151, 434–438.

[185] Nesic, S. Key issues related to modelling of internal corrosion of oil and gas pipelines.A review. *Corros. Sci.*2007, 49**,** 4308–4338.

[186] Revie, R. Oil, Gas Pipelines. In *Integrity and Safety Handbook*; John Wiley & Sons, Inc.: Hoboken, NJ, USA,2015.

[187] Papavinasm, S. *Corrosion Control in the Oil and Gas Industry*; Elsevier: Houston, TX, USA, 2013.

[188] Regulator, A.E. Report 2013-B: Pipeline Performance in Albarta, 1990–2012**;***Alberta Energy Regulator*: Calgary,AB, Canada, 2013.

[189] Kermani MB, Harrop D The impact of corrosion on the oil and gas industry. *SPE Production Facilities* 11, pp 186–190.1996.

[190] Nalli K, Corrosion and its mitigation in the oil and gas industry. An overview. *PM-Pipeliner Report.2010.*

[191] Ray JD, et.al; Use of reactive iron oxide to remove H2S from drilling fluid. *53rd Annu. Fall Tech. Conf. of AIME,* 1978.

[192] Martin RL, Use of electrochemical methods to evaluate corrosion inhibitors under laboratory and field condition. UMIST conference of electrochemical techniques, Manchester.1982.

[193] Weeter RF, Desorption of oxygen from water using natural gas for counter-current stripping. *J Petrol Technol* 17(5):51.1995.

[194] Hassani S, et.al; Flow loop study of NaCl concentration effect on erosion corrosion of carbon steel in CO2 saturated systems.*CORRO* ,2012.

[195] Sami A, et.al; Study synergy effect on erosion-corrosion in oil and gas pipelines. *Engng and Technol*.2008.

[196] Ossai CI, Advances in asset management techniques: an overview of corrosion mechanisms and mitigation strategies for oil and gas pipelines. *ISRN Corro* 570143. 2012.

[197] Brogden, S, et.al; The use of Engineering Polymers for Internal Corrosion Protection of Hydrocarbon Pipelines. *In Proceedings of the MERL Oilfield Engineering with Polymers Conference,* 2012.

[198] Davis, R.; Snider, B. Economically Mitigating Downhole Corrosion and Wear Failures with Thermoplastic Liners**;***NACE International:* Houston, TX, USA, 2017.

[199] Badeghaish, et.al;The Future of Nonmetallic Composite Materials in Upstream Applications; *Society of Petroleum Engineers (SPE):* Dallas, TX, USA, 2019.

[200] Gibson, et.al; Non-metallic pipe systems for use in oil and gas. *Plast. Rubber Compos***.** 2011, 40, 465–480.

[201] Wolodko, et.al;Application of Non-Metallic Materials in Oil Sands Operations, 1**;** *NACE International: Houston,* TX, USA, 2016.

[202] Comeau, A.; Bar, Y. *Significant Reduction of Corrosion Induced Pipe Failures in Oil Sands*/*SAGD Facilitiesusing PE-Xa Materials*; NACE International: Huston, TX, USA, 2016.

[203] CAPP.Mitigation of Internal Corrosion in Sour Gas Pipeline Systems**;** *CAPP: Calgary, AB, Canada,* 2009.

[204] Avery A and Martin S. Reinforced thermoplastic pipe Innovative technology for onshore field developments. In: *international conference on offshore mechanics & arctic engineering.* 2003, pp.787–794.

[205] Vlase, S.; et.al. Study on the Mechanical Responses of Plastic Pipes Made of High Density Polyethylene (HDPE) in Water Supply Network. *Appl. Sci.* 2020, *10*, 1658..

[206] Flexible think' Soluforce Offshore, www.soluforce.net, accessed, 2017.