*FUDMA Journal of Sciences (FJS)*
*ISSN online: 2616-1370*
*ISSN print: 2645 - 2944*
*Vol. 7 No. 5, October, 2023, pp 240 - 246*
*DOI: https://doi.org/10.33003/fjs-2023-0705-1927*

# INTERNET OF THINGS-BASED WIRELESS SENSOR NETWORK SYSTEM FOR EARLY DETECTION AND PREVENTION OF VANDALISM/LEAKAGE ON PIPELINE INSTALLATIONS IN THE OIL AND GAS INDUSTRY IN NIGERIA

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## ABSTRACT

The oil and gas industry in Nigeria faces significant challenges related to pipeline vandalism and leakage, leading to environmental damage, economic losses, and threats to human safety. Timely detection and prevention of such incidents are critical for ensuring the integrity and security of pipeline installations. This research proposes an Internet of Things (IoT)-based wireless sensor network system to address these challenges. The system utilizes a network of wireless sensors deployed along the pipeline infrastructure to monitor various parameters, including pressure, temperature, vibration, and gas emissions. The collected data is transmitted to a central server for analysis and decision-making, enabling early detection of vandalism or leakages. This research focuses on the design, implementation, and evaluation of the proposed system, considering the specific requirements and conditions of the Nigerian oil and gas industry.

**Keywords**: Internet of Things, wireless sensor networks, oil and gas

## INTRODUCTION

Crude oil remains Nigeria's major source of revenue generation to the country's government. Therefore, the country depends so much on what comes in as proceeds of the crude oil. Nigeria being a member of the World's oil-producing nations, OPEC and Africa's oil richest country, (a mono-economic country) struggle so hard to meet its production quarter of 2.3 million barrels per day (bpd). This inability of Africa's oil-rich country is particularly a result of an un-lasting security challenge in the oil production region. For over a decade now, the country has faced a lot of pipeline vandalism. This action does not only affect the revenue generation of the country but also contributes to the environmental pollution of the region. Crude oil theft leads to huge economic loss, human casualties, and environmental (water, air, and land) pollution in the world (Ordinioha, & Brisibe, 2013; UNDP (United Nations Development Programme), 2012; Anejionu, et al., 2015).

According to Ahmed (2022), it has been documented that oil spills have extensively infiltrated ecosystems, food chains, and essential resources like regulated water bodies, turning them into a significant source of distress for local communities and causing them to lose out on the environmental advantages they should enjoy.

It is documented that more than 10,000 instances of oil spills have had a significant impact on both the environment and the economic well-being of the population. From 1976 to 1996, there were a total of 4,647 oil spill occurrences in Nigeria, and an additional 2,097 incidents were reported between 1997 and 2001 (Anifowose, 2018). Moreover, there were approximately 3,600 oil spill events from 2001 to 2014, as reported by SPDC (2014a, 2014b). On average, the Niger Delta experiences around 600 oil spill incidents each year (Ogwus, 2021).

As stated by Anejionu and colleagues in 2015, the majority of oil spill occurrences are primarily due to pipeline explosions. These explosions typically happen as a consequence of the unintentional rupture of aging and inadequately maintained pipelines, deliberate acts of sabotage on oil facilities, particularly during activities like oil bunkering (illegally extracting hydrocarbon products such as crude oil, refined fuel, and condensate), and during drilling operations at new oil sites (Aibinu, et al., 2021; Rahman & Khan, 2023).

However, it is unfortunate that it is nearly impossible to provide human personnel to man the pipelines from exploration sites to the collection end (Sam, et al., 2016). Additionally, efforts such as employing acoustic travel and long-range monitoring systems have been implemented to prevent oil theft. These actions have indeed led to a current reduction in such incidents. Nevertheless, curtailing these perpetrators of crude oil theft remains a challenging endeavor, even though oil companies have improved their ability to detect oil leaks from remote pipelines due to the intricate and challenging nature of monitoring such leakages (Sun, et al., 2016; Yas & Al Qassab, 2023).

Addressing this issue requires innovative approaches for early detection and prevention. This research proposes an IoT-based wireless sensor network system as a potential solution to mitigate the risks associated with pipeline vandalism and leakage.

### Problem Statement

Pipeline vandalism and leakage are major concerns for the Nigerian oil and gas industry. Criminal activities, such as sabotage and theft, pose a significant threat to the security and integrity of pipeline installations. Moreover, natural factors, including corrosion and wear, contribute to the occurrence of leakages. The existing detection and prevention methods in place have limitations in terms of effectiveness, reliability, and timeliness. Therefore, there is a critical need to develop an advanced monitoring system that leverages IoT and wireless sensor networks to enable early detection and prevention of pipeline vandalism and leakage incidents.

The research objectives encompass the design of an IoT-based wireless sensor network system tailored for early detection and prevention of pipeline vandalism and leakage in Nigeria's oil and gas sector. This involves the deployment of a wireless sensor network along the pipeline infrastructure to monitor critical parameters like pressure, temperature, vibration, and gas emissions. Additionally, a central server and analytics framework are to be developed for data analysis, anomaly detection, and informed decision-making. The research seeks to evaluate the system's performance in terms of reliability, accuracy, timeliness, energy efficiency, and cost-effectiveness. Furthermore, it aims to offer recommendations for implementing this IoT-based system within the Nigerian oil and gas industry, while also suggesting potential avenues for future improvements.

**Related Literature**

As at May, 2016, crude oil production in Nigeria dropped to a record low of 1.2mbpd (Million Barrel Per Day) due to the attacks by militants on oil installations. This indicates 10% drop and has resulted in the lowest output by the country in more than thirty years (Adam & Alero, 2017). Similarly, oil companies in China lost more than three million Yuan yearly as a result of theft (Sun, et al., 2016).

Nigeria's government has at various times setup negotiation committees and military operations to tackle the security problem; however, this effort seems to have yielded fruitless results. In a similar note, the United Nations Environmental Programme (UNEP) releases a report of the Environmental Assessment of Ogoni-land in 2011. The report shows that there is depth degradation of bio-resource rich environments of the Niger Delta obviously, as a result of vandalism activities and natural weather effects on pipelines. Additionally, the report negates the erroneous operational The oil industry operators have concluded that in the Niger Delta region, the soil is enveloped by a clay layer, which effectively contains any oil percolation within the uppermost soil stratum (Wadhaj, et al., 2022; Sam, et al., 2016).

Furthermore, record available shows that over 10,000 during the period from 2001 to 2015, there were occurrences of oil spills and pipeline explosions, along with the flaring of over 350 billion cubic meters of gas (Anejionu, et al., 2015). Moreover, it was opined that the National Oil Spill Detection and Response Agency (NOSDRA) is ill equipped to handle the problem (Kerschner, et al., 2013).

Crude oil is transported from oil facilities on to barges or containers through pipeline of about 12,714KM in Nigeria. Transportation by pipelines has the advantages of; safety, high efficiency, low cost and stability. But considering the lengthy nature of the pipeline, it is nearly impossible to secure the pipeline especially at the time the crude oil flows. Oil companies have put measures in place to reduce the huge loss they suffer day- in-day-out. The companies are mandated to do so not only to reduce their financial loss but also to protect their social influence on the society (Wadhaj, et al., 2022).

Pipeline vandalism and leakage incidents in the oil and gas industry have been a recurring issue globally, and Nigeria is no exception. This section reviews the existing literature on pipeline vandalism and leakage, providing an overview of the causes, consequences, and frequency of such incidents. It also examines the environmental, economic, and social impacts of pipeline vandalism and leakage in Nigeria.

This section explores the current methods and technologies employed in the industry for the detection and prevention of pipeline vandalism and leakage. It discusses the strengths and limitations of these methods, including manual inspections, security patrols, surveillance systems, and leak detection systems.

The IoT and WSNs offer promising opportunities for enhancing pipeline monitoring and security.

WSN, or Wireless Sensor Network, is a technology that employs multiple sensor-equipped devices for cooperative data gathering. This technology functions by utilizing sensors, or nodes, to identify specific changes in physical parameters like wind, temperature, pressure, movement, and similar variables. Typically, a substantial number of these sensors are deployed to enhance coverage over a large area and optimize operational efficiency (Fasiuddin, et al., 2020; Aminu, et al., 2023). WSN is commonly applied in various domains, including ecological sensing such as forest fire detection, military reconnaissance for monitoring adversaries on the battlefield, traffic surveillance, healthcare, and more.

Conversely, IoT represents a global network that has the potential to create a novel application model built upon the internet. The Internet of Things enables an extensive array of endpoint devices such as RFID devices, sensors, and intelligent terminals, among others, within the real-world setting to interact with one another through the sensing environment.

A number of researches on IoT based WSN were carried out and a lot more are currently ongoing. Prominent among them include; Smart Farming System based on IoT and WSN (Mahbub, 2020; Oyubu, et al., 2022), IoT-Based Framework for Distant Surveillance of Physiological and Environmental Metrics (Gordana et al., 2018), Anomaly Detection System in IoT through WSN (Yu et al., 2020) and Hybrid Secure Routing and Monitoring Mechanism in IoT based WSNs (Deebak & Al-turjman, 2019).

Various types of sensor nodes (motion sensors, temperature/relative humidity sensors, barometric pressure sensors, soil moisture sensors, pH sensors, etc) were modelled. However, it was noticed that this and many other researches alike lack important components that can enable the systems make smarter decisions. These components are Artificial Intelligence and Data Mining Algorithms (Mahbub, 2020).

Within the IoT sensor network, the sensing nodes could be situated in an autonomous, ever-changing environment characterized by limited capabilities, constrained resources, and unpredictable conditions (Bei, et al., 2018).

Therefore, marrying the two technologies together (IoT and WSN) will make a perfect match in the design and implementation of an intelligent system that will be used to detect, monitor and respond to leakages resulting from weather and/or illegal taps in real time. This technology will help us to understand the current situation and propose a new system and to compare the two with the intent of providing lasting solution to the problem.

## MATERIALS AND METHODS

The sensor networks used for monitoring natural gas pipelines consist of numerous sensor nodes, sinks, and a control and management centre. The entire network operates under a clustering structure, as illustrated in Figure 1 below. Sensor nodes, which are strategically placed along the pipeline, are tasked with gathering signals and processing data. The processed results are then transmitted to the sink through a multi-hop route. Communication between sensor nodes in the monitoring network is conducted within the pipeline.

The sink, serving as the leader of its cluster, assumes responsibility for managing the sensor nodes in its cluster, aggregating processing outcomes to make final decisions, and determining the location in case of an attack or a leak. Ultimately, the diagnostic results are forwarded to the control and management centre, which evaluates whether an alert for a potential attack should be issued.

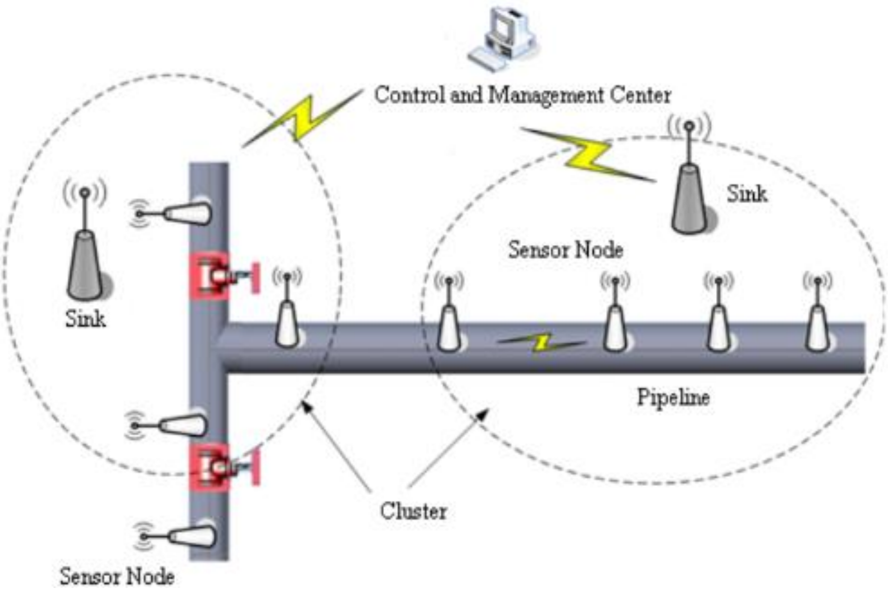

Figure 1. Architecture of pipeline monitoring sensor networks

**Sensor Selection and Deployment Strategy**

This section focuses on the selection of appropriate sensors for the monitoring of pipeline parameters such as pressure, temperature, vibration, and gas emissions. It discusses the considerations for sensor types, accuracy, reliability, and compatibility with IoT platforms. Furthermore, it outlines the optimal deployment strategy, including sensor placement along the pipeline infrastructure.

**Sensor Selection**

When it comes to monitoring pipeline parameters such as pressure, temperature, vibration, and gas emissions, it is essential to select appropriate sensors that can accurately and reliably measure these variables.

We deployed Pressure Transducers/Transmitters to convert pressure into electrical signals so as to monitor pipeline pressure. They provided continuous pressure readings. Thermocouples were also used for temperature measurement. They consist of two dissimilar metal wires that generate a voltage proportional to the temperature difference between the measurement point and the reference point. We also made use of Accelerometers to measure vibration and were applied to detect pipeline vibrations caused by factors like fluid flow, structural stress, or external forces. They convert mechanical vibrations into electrical signals and provide data on vibration intensity and frequency. Lastly, Gas Detectors were also deployed crucially for monitoring gas emissions in pipelines to ensure safety and environmental compliance.

It's worth noting that there are other types of sensors available for these parameters, and the choice of sensor depends on factors such as the specific requirements of the pipeline, environmental conditions, accuracy needed, and regulatory standards.

When considering sensor types, accuracy, reliability, and compatibility with IoT platforms, there are several important factors to take into account. This research makes the following key considerations:

In choosing the sensor types, we first considered purpose to determine the specific sensing requirements for our IoT application. Thus, temperature, humidity, pressure, motion, proximity, light, and gas sensing were detected.

Secondly, the operating environment where the sensors are deployed (outdoor) there by exposing them to extreme temperatures, humidity levels, dust and water.

Another critical consideration was to evaluate power consumption, the power requirements of the sensors are low so as to have high impact battery life in IoT devices.

On the accuracy considerations, our research was able to take care of issues such as Measurement Range to ensure that the sensor can measure values within the required range; Calibration to maintain accuracy over time; Resolution to determine the smallest measurable change in the sensed parameter. Higher resolution enables more precise measurements.

Furthermore, sensors selected supports common IoT communication protocols such as MQTT, CoAP, or HTTP, allowing seamless integration with IoT platforms.

**Guidelines for Sensor Placement**

The optimal deployment strategy for sensors along a pipeline infrastructure can vary depending on several factors, including the specific goals, the type of pipeline, and the operational requirements. However, this research was guided by; critical areas- areas along the pipeline that require monitoring. These areas include potential leakage points, valve locations, junctions, compressor stations, and other points of interest where early detection of issues is crucial; Coverage and redundancy- sensors were strategically placed to provide comprehensive coverage of the pipeline infrastructure. Redundancy is important to minimize blind spots and provide backup data; Leak detection- Sensors were installed at regular intervals along the pipeline to detect leaks promptly; Environmental monitoring- Sensors were included to monitor environmental conditions along the pipeline, such as temperature, humidity, and soil conditions. These sensors help to identify potential risks that could affect pipeline integrity, such as temperature variations or soil movement; Security and intrusion detection- Sensors were placed to detect unauthorized access or potential security breaches, especially at access points, valves, or critical infrastructure locations.

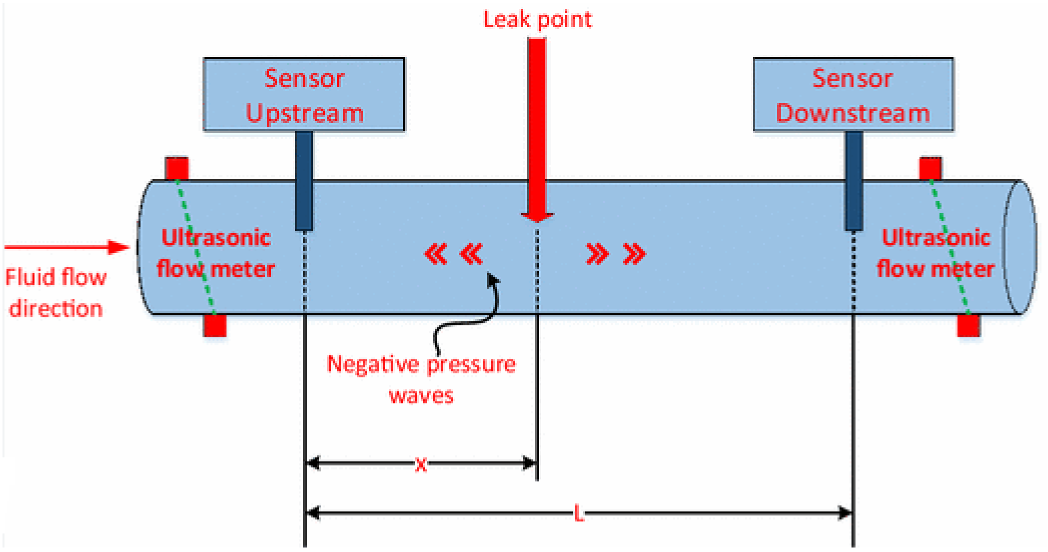

Figure 2. Sensor Deployment Strategy

This placement strategy was developed in due consultation with pipeline experts, engineers, and relevant industry standards and in accordance with regulatory guidelines.

**Communication Protocols**

The chosen communication protocols, such as MQTT or LoRaWAN, ensure reliable and efficient data transmission within the wireless sensor network. Data aggregation, compression, and encryption techniques are employed to optimize data transmission and ensure secure communication. Robust communication protocols allow for seamless transmission of sensor data to the central server for further analysis and decision-making.

To ensure suitability and efficiency some guidelines are very effective in choosing communication protocols: They include:

i. Scalability and Range.
ii. Power Consumption.
iii. Data Volume and Bandwidth.
iv. Reliability and Latency.
v. Security.
vi. Network Topology.
vii. Integration and Interoperability.
viii. Cost

Ultimately, the selection of communication protocols and network topology should be based on a thorough analysis of the specific requirements, constraints, and goals of the pipeline monitoring system, ensuring that it meets the desired performance, reliability, security, and scalability criteria.

**Data Transmission Mechanism**

There are several mechanisms available for transmitting sensor data from deployed sensors to a central server in an IoT-based pipeline monitoring system. The choice of mechanism depends on factors such as distance, power requirements, available infrastructure, data volume, and desired communication technology. Common mechanisms include:

i. Wired Connections.
ii. Wi-Fi.
iii. Cellular Networks.
iv. Low-Power Wide-Area Networks (LPWAN).
v. Zigbee and Z-Wave.
vi. Bluetooth and Bluetooth Low Energy (BLE).
vii. Satellite Communication.
viii. Hybrid Approaches

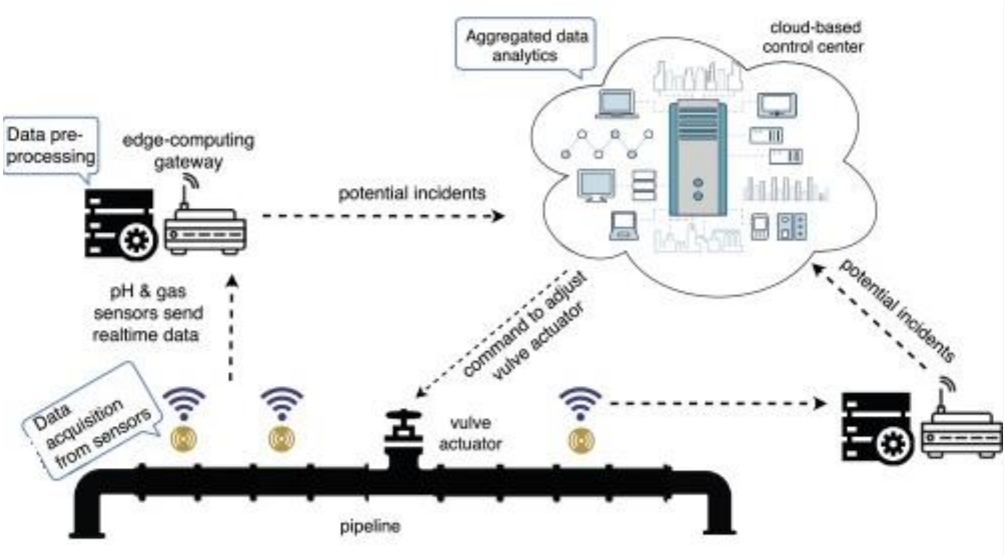

Figure 3. Data Flow Diagram

When selecting the mechanism for transmitting sensor data, it is important to consider factors such as coverage, data volume, power consumption, reliability, security, and cost, as well as the specific requirements and constraints of the pipeline monitoring system.

### Data Processing and Analytics

Data processing methods, including filtering, normalization, and outlier detection, are employed to pre-process the collected sensor data. An analytics framework is developed for real-time data analysis, anomaly detection, and decision-making. This facilitates timely detection and prompt response to potential vandalism or leakage incidents. Advanced analytics techniques, such as machine learning algorithms, can be utilized to detect patterns and anomalies in the sensor data.

### User Interface Design

The user interface is designed to provide stakeholders with a comprehensive view of the pipeline status, sensor readings, and alerts. Real-time visualization, historical data analysis, and customization options are incorporated to enhance usability and facilitate informed decision-making. Graphical representations, charts, and maps can be utilized to present sensor readings and alert notifications in an intuitive and user-friendly manner.

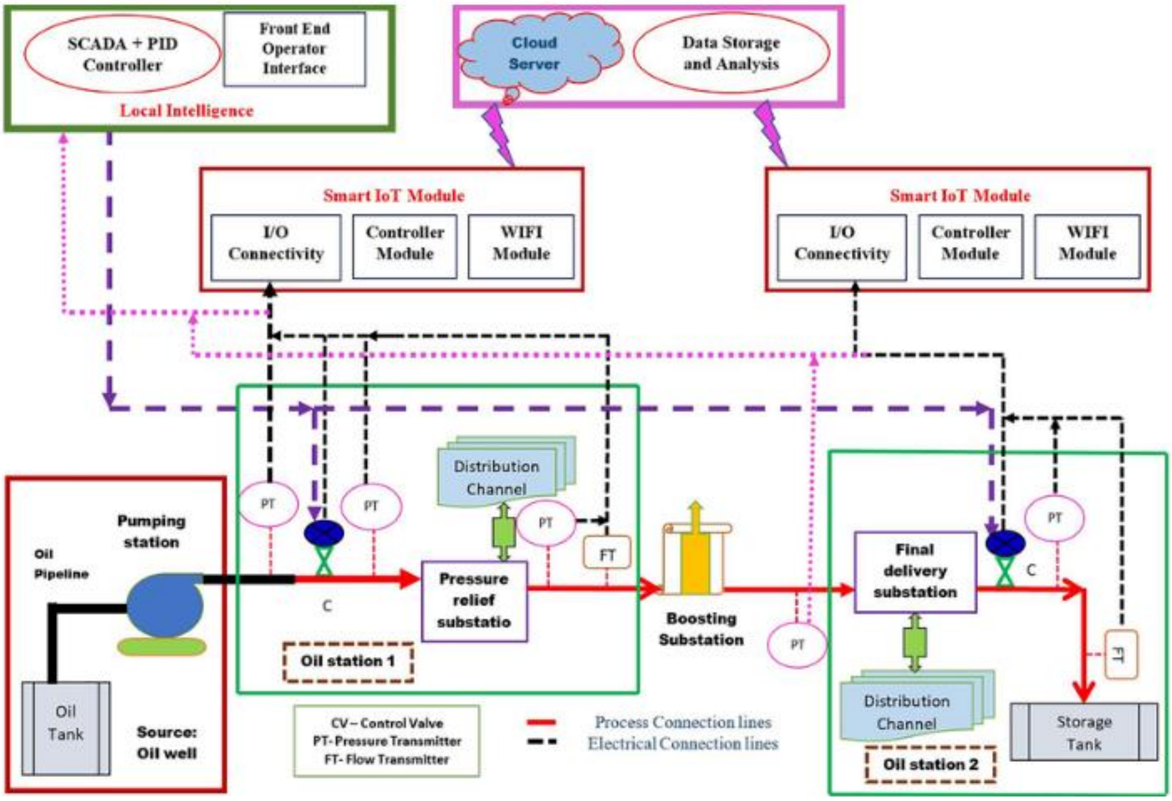


Figure 4. User Interface Design Mockup Diagram

### System Integration and Testing

The hardware components, including sensors, microcontrollers, wireless modules, and power sources, are integrated to form a cohesive system. The software modules for data collection, communication, data processing, analytics, and user interface are developed and integrated. Rigorous testing procedures are conducted to ensure the functionality, reliability, and scalability of the IoT-based system. This includes testing the communication between the sensors and the central server, validating the accuracy and timeliness of the alert generation, and evaluating the overall system performance in different scenarios.

## RESULTS AND DISCUSSION

To evaluate the individual strengths (detection or prevention) of the methods of pressure point analysis (PPA), the gradient-based method (GM) and the negative pressure wave method (NPWM), we conducted comprehensive simulations using the Network Simulator 3 (NS3) platform to model crude oil propagation and leakages within a single horizontal transmission pipeline segment designed for one-phase flow. The objective of our simulations was to determine the optimal node placement that would enable efficient detection of small to large-sized leaks and assess the performance of NPWM and GM under these conditions. In Table (I) below, we provide an overview of the simulation parameters.

**Table I: Simulation Parameters**

| *Type* | *Transmission Line* |
|---|---|
| *Material* | Carbon Steel |
| *Length* | 20km |
| *Wall thickness* | 0.323m |
| *Inside diameter* | 0.61m |
| *Height/elevation* | 0m |
| *Oil kinetic viscosity* | 2.90mm$^2$/s |
| *Temperature* | 50$^0$C |

| | |
|---|---|
| *Oil density* | 837kg/m$^2$ |
| *Intel Pressure* | 1000psi |
| *Reynolds no* | 1950 |
| *Velocity* | 2m/s |
| *Oil modulus elasticity* | 1.85 * 10$^5$psi |
| *Carbon steel modulus elasticity* | 3 * 10$^6$psi |
| *Gravitational force* | 9.81m/s |
| *Constant* | 2.718 |
| *Wave speed* | 14.1m/s |
| *Coefficient of friction* | 0.033 |
| *Packet size* | 32bytes |
| *Data rate* | 1Kbps |

In these initial simulations, we focused on assessing NPWM and PPA for leak detection, and NPWM and GM for leak localization. It is essential to note that, as part of this primary test, we did not introduce any factors that could lead to communication failures, node failures, or infrastructure issues. Our simulations were conducted under ideal conditions for each method, enabling a clear evaluation of their effectiveness.
Furthermore, we carried out leakage localization in a centralized manner by utilizing data collected from all sensor nodes. These preliminary results from our simulations serve as a foundational basis for future comparative analyses between the centralized and distributed versions, which will be explored in subsequent research efforts.

## CONCLUSION

The system design and simulations presented in this report represent a significant step towards addressing the pervasive issue of pipeline vandalism and leakage in the Nigerian oil and gas industry. By employing state-of-the-art IoT-based wireless sensor network systems, we aim to revolutionize pipeline security, enable real-time monitoring, and facilitate timely detection and responses to potential threats.
In conclusion, this research work is expected to contribute significantly to the advancement of pipeline security and safeguarding the environment in the Nigerian oil and gas sector. We look forward to further exploring the potential of distributed sensor networks and conducting a comparative analysis of centralized and distributed systems in future studies.

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