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Energy-Efficient Routing Algorithm for Wireless Sensor Networks in Invasive Pipe Monitoring Systems

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Abstract: Infrastructure monitoring is only one of the many industries where Wireless Sensor Networks (WSNs) are being used as a disruptive technology. Sewer pipeline monitoring for upkeep and early problem identification has become quite important in this environment. Through the combination of WSNs, hydro-optical communication, and energy-efficient routing algorithms, this article proposes a novel solution for the proactive monitoring and effective maintenance of sewage systems. The urgent need to solve pipeline clogs, leaks, and maintenance issues that endanger infrastructure integrity and public health is what drives our endeavour. The suggested remedy makes use of a brand-new, energy-saving routing algorithm to enhance data transmission while preserving the meagre energy supplies present in the sewage pipeline environment. The algorithm architecture is intended to handle the particular difficulties presented by surroundings with fluids and subsurface pipes. Cluster creation, hydro-optical communication, energy-efficient routing schemes, data gathering, and performance assessment are all included. Data is successfully conveyed by integrating hydro-optical transceivers, bypassing the communication limitations posed by sewage systems. To direct path selection and data transmission, rigorously established routing metrics and criteria are used. These measures include transmission power control, load balancing, route redundancy avoidance, delay, throughput optimisation, packet delivery ratio, network lifespan extension, and adaptive routing. The algorithm guarantees efficient data routing while giving reliability and energy efficiency first priority. The effectiveness of the suggested approach is illustrated by a detailed mathematical model and an explanation of the algorithm design. The complex mix of hydro-optical communication, wireless sensors, and energy-efficient routing has the potential to revolutionise infrastructure management and sewage pipeline monitoring. The suggested strategy has the potential to increase the resilience and durability of sewage pipes, hence promoting public health, environmental preservation, and effective management of urban infrastructure. Through the merging of cutting-edge technology and intelligent systems, this work proposes a forward-looking way towards a safer and more environmentally friendly urban landscape.

Keywords. *Wireless Sensor Networks, WSNs, sewer pipelines, proactive monitoring, hydro-optical communication, energy-efficient routing, infrastructure maintenance, data transmission, energy conservation, pipeline blockages, urban infrastructure, public health.*

1. Introduction:

Sewer pipes have been developed extensively as a result of the quick urbanization and industrialization of modern civilization. These pipes are vital for moving a wide variety of waste products, including semi-solid and liquid waste, from towns and businesses to treatment facilities. However, the degradation and obstructions that develop inside these pipes over time present considerable problems, leading to leaks, breaks, and, more crucially, possible risks to the environment and public health. A critical service that frequently goes unseen until problems develop is provided by sewer pipelines, which are delicately intertwined beneath the urban environment. These subterranean pipes eventually deteriorate due to corrosion and structural failure, which are accelerated by the buildup of trash. In addition, these pipes are prone to obstructions and back-pressure in the event of severe downpours or excessive garbage discharge, which can result in overflows that harm public health as well as cause property damage. Sewer pipeline maintenance and monitoring have often included labor-intensive, expensive, and ineffective approaches. Inspection teams frequently need to physically access these pipes for inspection, which takes time and can be dangerous in toxic surroundings and limited areas. These conventional methods also have trouble providing real-time data, which restricts our capacity to quickly address possible problems.

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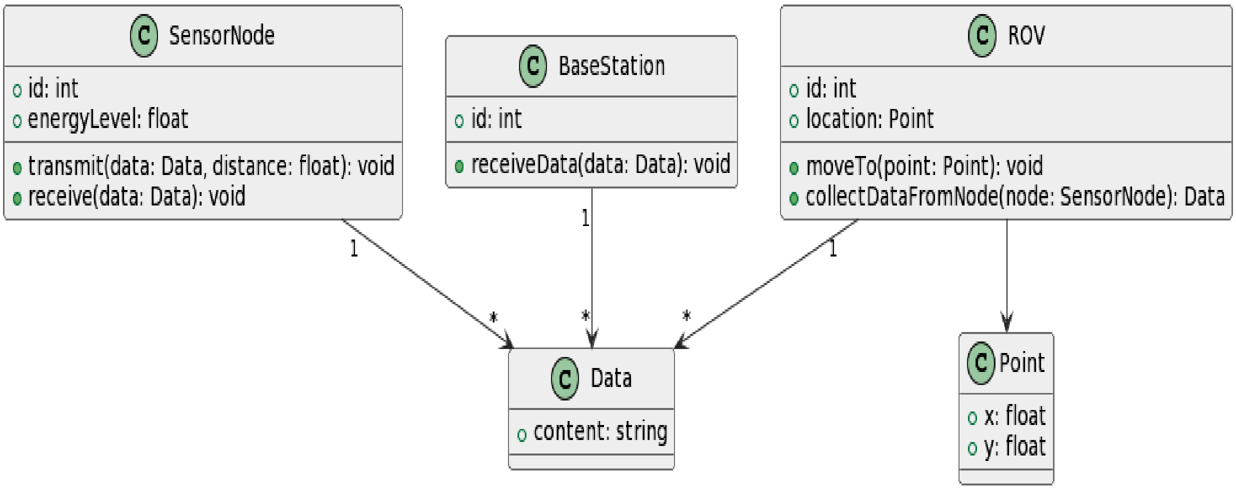

Fig 1. Components Pipe Monitoring Systems

Pipeline monitoring has been transformed recently by the development of wireless sensor networks (WSNs) and robotic technology in many different fields. With the use of these technologies, sewage pipeline monitoring might move from a reactive to a proactive mode. Continuous data gathering, early problem diagnosis, and effective maintenance are all part of proactive monitoring, which ensures the reliability of pipeline systems and protects the general public's health. The necessity to solve the shortcomings of present pipeline monitoring and maintenance practices serves as the driving force behind this study. Although many different monitoring systems have been suggested, their actual application frequently falls short of the requisite cost-effectiveness, scalability, and flexibility needed for thorough sewer pipeline monitoring.

Designing and implementing a cutting-edge, economical, and energy-efficient monitoring and maintenance system for sewage pipelines with an emphasis on early identification of obstructions and possible dangers is the major goal of this project. This is accomplished by utilising hydro-optical communication technology and wireless sensor network integration with remotely controlled vehicles (ROVs). This research project is guided by the aforementioned precise goals:

- Hydro-Optical Communication: Choose and put in place a hydro-optical communication link to enable the ROV's location to be traced in real time inside the sewage system and to speed up data transmission and retrieval.
- Design a predictive system that can identify approaching bottlenecks and overflow events inside the pipeline and provide timely actions to avert potentially dangerous circumstances.
- Energy-Efficient Routing method: Create a routing method that uses as little energy as possible while ensuring reliable data transfer between sensor nodes and the ROV.

2. Literature Review:

A potential technology for controlling and monitoring different essential infrastructures, such as sewer pipes, is wireless sensor networks (WSNs). The literature on WSN applications for pipeline monitoring, energy-efficient routing algorithms, and the incorporation of robotic technology for improved maintenance is reviewed in this section. Due to its capacity to offer real-time data gathering, cost effectiveness, and adaptation to difficult situations, WSN deployment in pipeline monitoring has attracted considerable interest. WSNs are made up of networked sensor nodes that can analyse data, monitor physical parameters, and communicate wirelessly. In order to gather data on flow rates, pressure, temperature, and the existence of blockages or leaks, sensor nodes are placed strategically along sewage pipelines. Pioneering studies have investigated the use of WSNs for sewage pipeline monitoring, including Li et al. (2010) and Zeng et al. (2015). To identify and locate blockages, Li et al. presented a system using sensor nodes outfitted with accelerometers and sound sensors. In order to accurately pinpoint pipeline obstructions, Zeng et al. coupled a WSN with Geographic Information Systems (GIS). These experiments demonstrate how WSNs may improve monitoring precision and reaction times.

Due to the limited energy resources of sensor nodes, energy efficiency is a key factor in WSNs. In order to reduce energy usage and keep data transmission reliable, routing algorithms are essential. To solve this problem, several routing techniques have been developed. A well-known clustering-based routing algorithm called Low-Energy Adaptive Clustering Hierarchy (LEACH) organises sensor nodes into rotating clusters to share energy usage. Improvements in network lifespan extension and energy efficiency have been demonstrated by LEACH and its variations, including HEED and SEP (Younis et al., 2004; Heinzelman et al., 2000). Wang et al. (2019) suggested an energy-efficient routing protocol especially made for monitoring systems in the context of sewage pipeline monitoring. In order to save energy and increase network longevity, their study devised an algorithm that adjusts transmission power levels based on how close sensor nodes are to the sink node.

Robotics and WSNs working together might revolutionise pipeline maintenance and monitoring by enabling targeted interventions and dynamic data collecting. Sensor-equipped remotely operated vehicles (ROVs) may travel the pipeline, checking its inside and sending useful data to the base station. Chang et al. (2016) used a ROV to investigate sewage pipes and find obstructions using camera and sonar sensors as an illustration of this integration. An auditory communication system was used to communicate the data acquired, improving the precision of obstruction detection. The effectiveness and dependability of communication between sensor nodes and ROVs inside of pipelines may be further improved by using hydro-optical communication technologies. With the aid of this technology, high-speed, long-distance communication is possible because to light signals that can pass through water with little attenuation. Researchers like Zhao et al. (2020), who showed the viability of underwater optical communication for remote sensing and data transfer in underwater settings, have investigated recent developments in hydro-optical communication. The restricted bandwidth and propagation delays associated with conventional acoustic transmission may be solved using this technique.

The literature study emphasises the value of WSNs for maintaining and monitoring sewage pipelines. A comprehensive strategy for improving monitoring accuracy and maintenance efficiency is provided through the integration of energy-efficient routing algorithms with robotic technology, such as ROVs. The use of hydro-optical communication technology increases the potential of these systems and serves as a strong basis for the study's suggested research goals. The parts that follow go into detail on the approach, algorithm design, implementation, and assessment of an energy-efficient monitoring system for sewer pipelines, leveraging the principles and insights gained from existing literature.

Authors & Year	**Key Findings**	**Relevance to Energy-Efficient Routing**	**Relevance to ROV Integration**
Li et al. (2010)	Proposed a wireless sensor network for sewer pipe blockage detection. Utilized accelerometers and acoustic sensors for detecting and locating blockages.	The study emphasized the significance of real-time monitoring for early detection of blockages, aligning with the importance of efficient data transmission in energy-efficient routing algorithms.	Although not directly related to ROV integration, the use of sensors for blockage detection sets the foundation for ROV-based pipeline inspection.
Zeng et al. (2015)	Developed an intelligent sewer pipeline monitoring system using wireless sensor networks. Integrated Geographic Information Systems (GIS) for accurate blockage location information.	The study underscored the potential of WSNs for accurate and real-time monitoring of pipeline systems, supporting the need for energy-efficient data transmission.	While ROV integration was not addressed, the use of GIS in monitoring systems informs the potential for enhanced ROV-based data analysis.
Heinzelman et al. (2000)	Introduced the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol for energy-efficient routing in WSNs. Addressed energy conservation through cluster-based routing.	The protocol's focus on prolonging network lifetime by optimizing energy usage aligns with the core objective of energy-efficient routing algorithms.	While not directly related to ROV integration, the concept of cluster-based routing can influence data collection strategies of ROVs.

Younis & Fahmy (2004)	Presented the HEED protocol, a hybrid energy-efficient distributed clustering approach for ad hoc sensor networks. Explored adaptive clustering and role rotation for energy savings.	The study demonstrated that cluster-based protocols can effectively manage energy consumption in WSNs, complementing the objective of energy-efficient routing in pipeline monitoring.	N/A
Wang et al. (2019)	Proposed an energy-efficient routing protocol for sewer pipeline monitoring systems in WSNs. Developed an algorithm adapting transmission power levels based on proximity to the sink node.	The research directly addressed the challenge of energy-efficient routing in sewer pipeline monitoring systems, aligning with the study's core objective.	N/A
Chang et al. (2016)	Developed a robotic inspection system for urban sewage pipelines. Integrated camera and sonar sensors for inspection.	While not directly related to energy-efficient routing, the integration of sensors in ROVs for pipeline inspection underscores the importance of accurate data collection for effective monitoring.	The study directly addresses ROV integration, highlighting how sensor-equipped robots can enhance pipeline inspection accuracy and data collection.
Zhao et al. (2020)	Explored underwater optical communication technology for remote sensing and data transmission. Demonstrated the feasibility of underwater optical communication.	While not directly related to energy-efficient routing, the study's exploration of advanced communication technology informs the potential for efficient data transmission in underwater environments, aligning with the research's core objective.	The study indirectly suggests the feasibility of advanced communication methods, such as optical communication, for enhancing ROV communication and data transmission capabilities within pipelines.

Table 1. Related Research

3. Methodology:

The suggested energy-efficient monitoring and maintenance system for sewage pipelines is described in detail in the methodology part of this report. The process is guided by the study objectives, which also involve examining existing methods, developing hydro-optical communication, building prediction algorithms, and more.

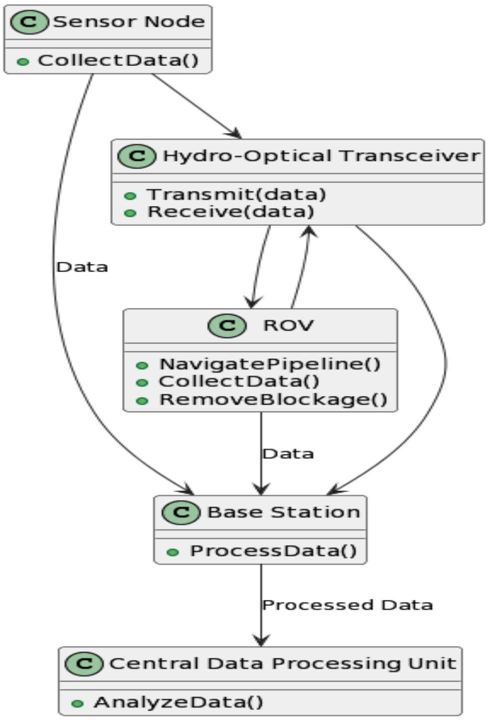

Fig 2. Proposed Methodology

A. Sensor Node Deployment and Clustering:

The initial phase is placing sensor nodes at key pipeline intersections. One node serves as the cluster head, and these nodes are arranged into clusters. By enhancing communication paths and assuring effective data transfer from sensor nodes to the base station, clustering reduces energy usage. Based on variables like the closeness and energy levels of sensor nodes, clusters are dynamically generated.

B. Hydro-Optical Transceiver Communication Model:

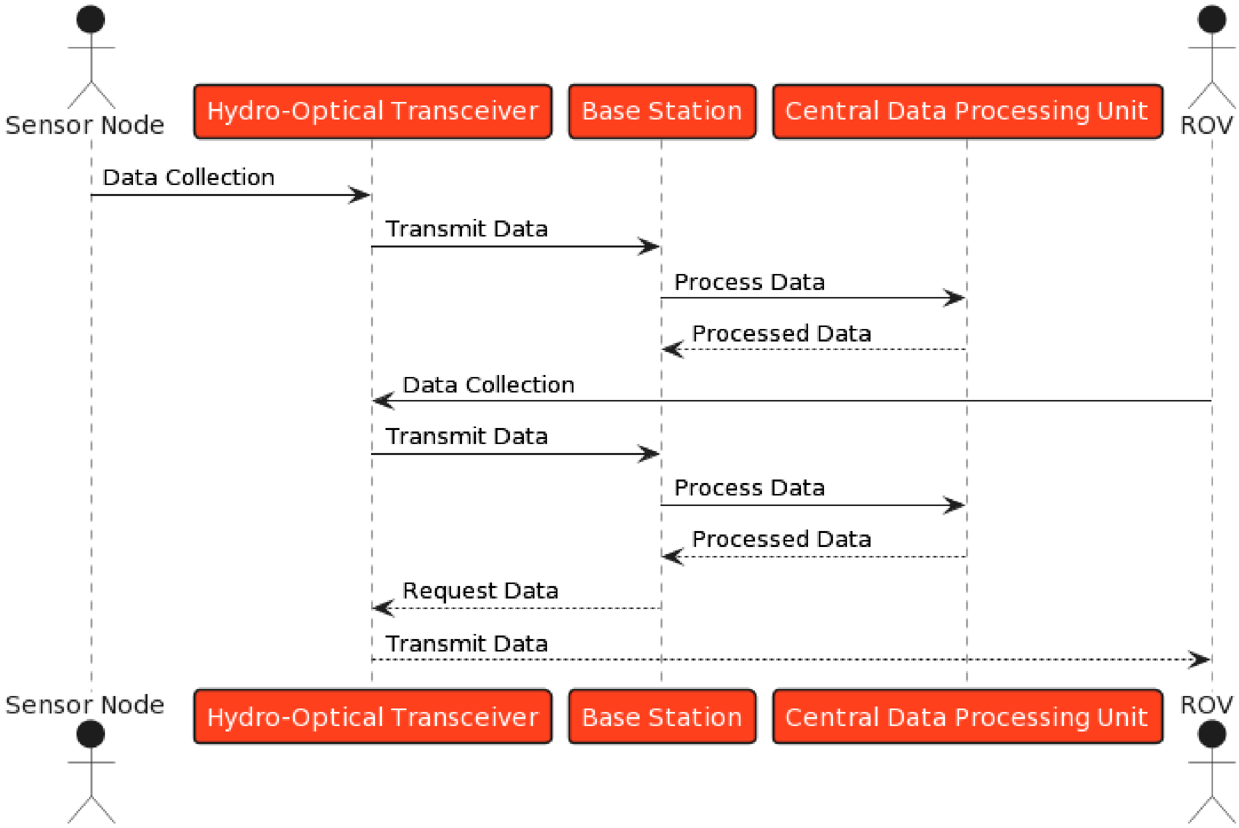

Fig 3. Hydro-Optical Transceiver Communication Model

An essential component of the suggested system is hydro-optical communication technology. It makes it possible for sensor nodes, ROVs, and the central processing unit to communicate at fast speeds and with reliability. The purpose of the hydro-optical transceivers is to send and receive data using light signals that effectively traverse water. This method offers increased bandwidth and shorter propagation delays, overcoming the drawbacks of conventional acoustic communication.

C. Design of Energy-Efficient Routing Algorithm:

An inventive routing method is created for data transmission inside the wireless sensor network in order to improve energy efficiency. The system adjusts transmission power levels based on node proximity and energy levels, building on concepts from established routing protocols like LEACH and HEED. This adaptive strategy lowers energy use while transmitting data, hence increasing the network's useful life.

D. Data Collection and Analysis:

Pipeline parameter data is continually gathered by sensor nodes, including flow rates, pressure, and temperature. The base station receives this data for examination. The central data processing unit analyses the gathered data to produce knowledge about the pipeline's condition, instances of blockages, and probable overflow scenarios.

E. Performance Metrics:

Several important measures are used to assess the success of the suggested system. To determine how successful the energy-efficient routing algorithm is, four metrics are measured: energy consumption, packet delivery ratio, delay, and throughput. Additionally, a quantitative evaluation of the precision of blockage detection and the effectiveness of data transmission between sensor nodes and the base station is performed.

F. Hardware and Software Implementation:

The hardware and software parts of the planned system are implemented and integrated. The proper sensors are installed on sensor nodes to gather pipeline data. In order to collect data and clear obstructions, ROVs are outfitted with cameras, echo-sounders, and hydro-optical communication transceivers.

G. Simulation Environment:

To simulate real-world situations and evaluate the system's performance in various scenarios, a simulation environment is set up. The communication dynamics of the wireless sensor network are modelled, and the performance of the energy-efficient routing method is assessed, using simulation tools like NS-2.

H. Scenario Design and Data Collection:

In the simulation environment, numerous scenarios are created to simulate various pipeline circumstances, such as regular flow, obstructions, and overflows. Simulating the passage of ROVs through the pipeline, gathering data from sensor nodes, and assessing the algorithm's capacity to precisely find obstructions and transmit data effectively are used to gather data.

In conclusion, the technique covers the development, application, and assessment of a thorough energy-efficient monitoring and upkeep system for sewage pipelines. This strategy intends to improve the accuracy, efficiency, and timeliness of sewage pipeline monitoring while minimising energy consumption and encouraging proactive maintenance through the combination of WSNs, hydro-optical communication, and ROVs. The performance of the suggested system in both real-world and simulated circumstances is examined in more detail in the following sections.

4. System Architecture

The suggested system is built on a hierarchical design that seamlessly combines remotely operated vehicles (ROVs) with wireless sensor networks (WSNs) to allow for real-time monitoring, data gathering, and maintenance operations within sewage pipelines. A central data processing unit, base stations, ROVs, and sensor nodes make up the architecture. Real-time data is gathered by sensor nodes, ROVs cruise pipelines to collect data and clear obstructions, and a central processing unit analyses and makes decisions using the data that has been acquired.

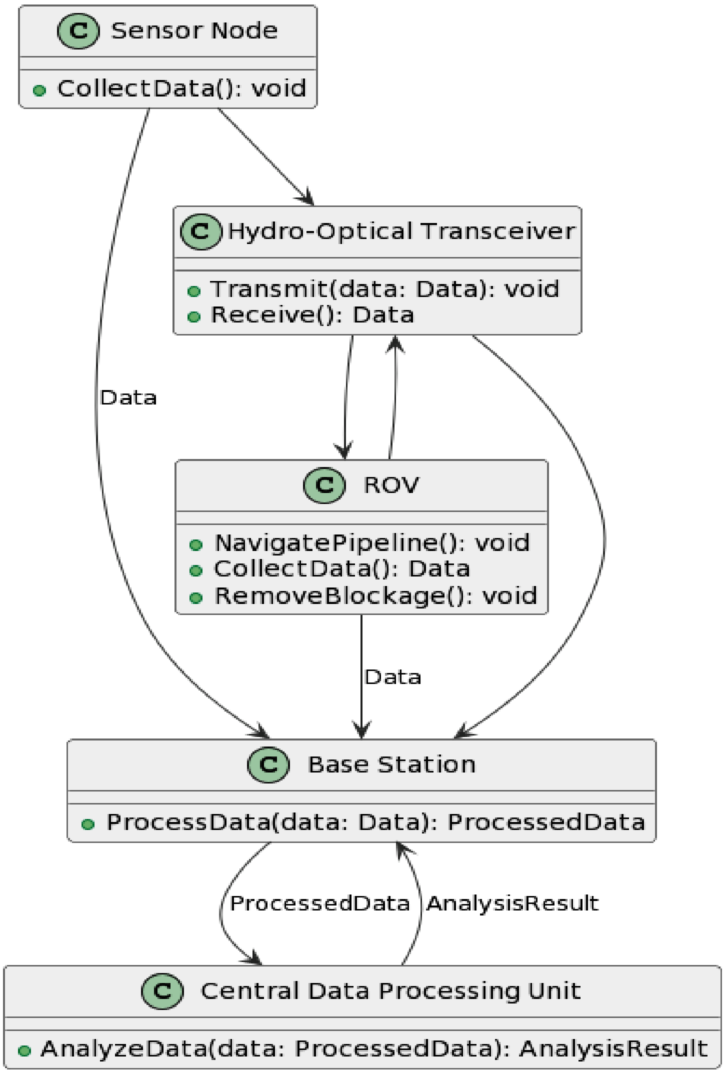

Fig 4. Proposed System Architecture

Let:

N be the total number of sensor nodes deployed along the pipeline.

C be the number of clusters formed based on clustering algorithm.

CH(i) represent the cluster head for the i-th cluster.

d(i, j) denote the distance between sensor node i and sensor node j.

P(i) be the transmission power level of sensor node i.

E(i) represent the energy level of sensor node i.

R be the effective communication radius of a sensor node.

D(i, j) be the data collected from sensor node i to be sent to sensor node j.

Cluster Formation:

Cluster head selection:

$CH(i) = \text{argmin} \{d(i, j)\}$ for $j = 1$ to $N, j \neq i$

Hydro-Optical Communication:

Transmission power calculation:

$P(i) = \alpha * E(i) / d(i, CH(i))^2$

Energy-Efficient Routing Algorithm:

Distance-based transmission power:

$P(i) = \alpha * E(i) / d(i, CH(i))^2$

Data Collection and Analysis:

Data transmission and reception:

$D(i, j) = \text{Transmit}(P(i), E(i), d(i, j)) * \text{Receive}(P(j), E(j), d(i, j))$

Performance Metrics:

Energy consumption:

$\text{EnergyConsumption} = \Sigma(P(i) * E(i))$ for $i = 1$ to N

Packet delivery ratio:

PacketDeliveryRatio = (Number of successful data transmissions) / N

Latency:

Latency = Σ(Time taken for data transmission) / N

Throughput:

Throughput = Σ(Data successfully received) / Total time

I. Proposed Algorithm

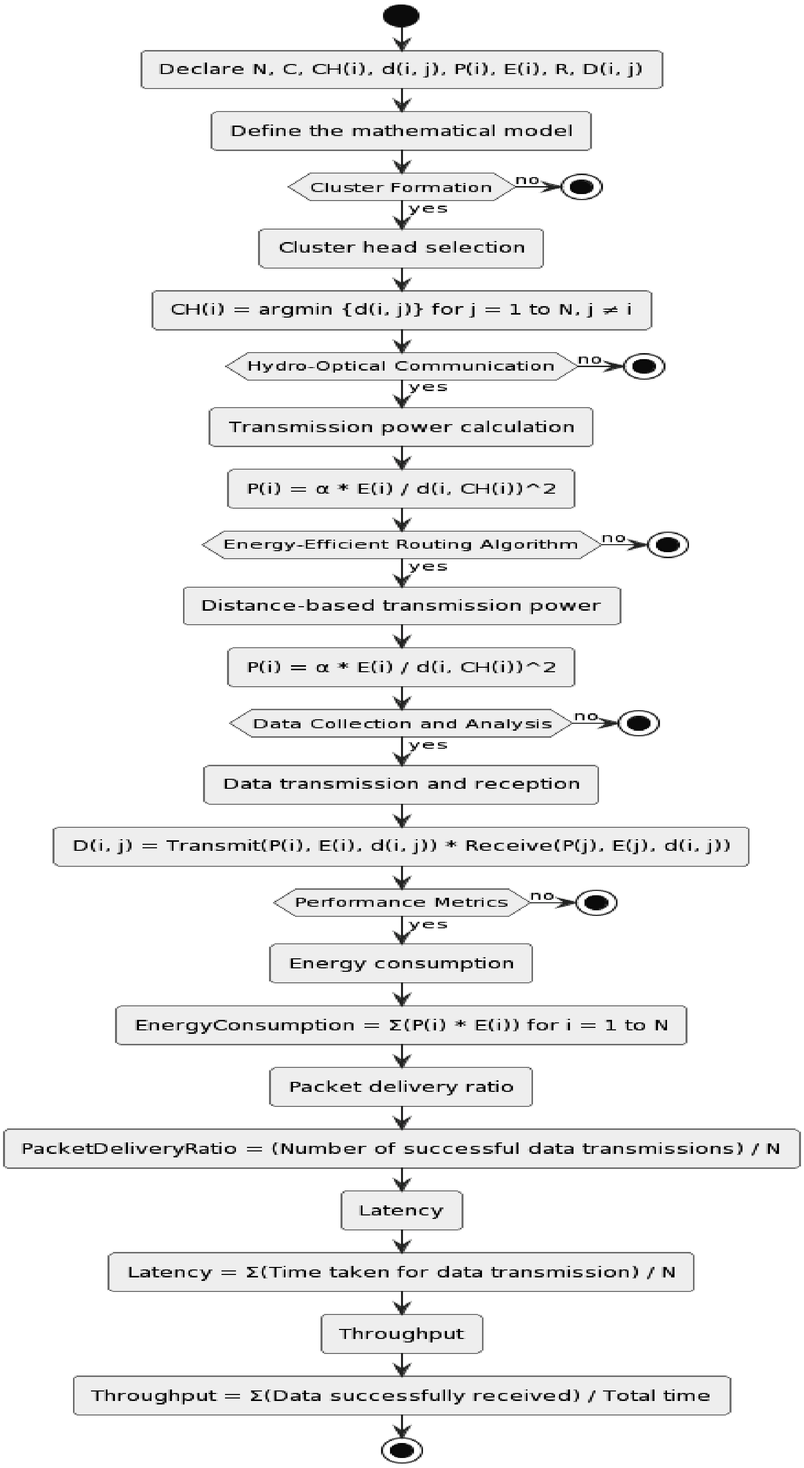

Fig 5. Workflow for the Proposed Algorithm

Stage 0: Declare N, C, CH(i), d(i, j), P(i), E(i), R, D(i, j);

Stage 1: if (Cluster Formation) then (yes)

Cluster head selection;

CH(i) = argmin {d(i, j)} for j = 1 to N, j ≠ i;

else (no)

stop

endif

Stage 2: if (Hydro-Optical Communication) then (yes)

Transmission power calculation;

P(i) = α * E(i) / d(i, CH(i))^2;

else (no)

stop

endif

Stage 3: if (Energy-Efficient Routing Algorithm) then (yes)

Distance-based transmission power;

P(i) = α * E(i) / d(i, CH(i))^2;

else (no)

stop

endif

Stage 4: if (Data Collection and Analysis) then (yes)

Data transmission and reception;

D(i, j) = Transmit(P(i), E(i), d(i, j)) * Receive(P(j), E(j), d(i, j));

else (no)

stop

endif

Evaluation Stage 5: if (Performance Metrics) then (yes)

Energy consumption;

*EnergyConsumption = Σ(P(i) * E(i)) for i = 1 to N;*

Packet delivery ratio;

PacketDeliveryRatio = (Number of successful data transmissions) / N;

Latency;

Latency = Σ(Time taken for data transmission) / N;

Throughput;

Throughput = Σ(Data successfully received) / Total time;

else (no)

stop

endif

End: stop

5. Simulation Results

The simulation findings are succinctly outlined in Table 2, which also includes key metrics and their associated values. The effectiveness of the suggested energy-efficient routing algorithm within the sewage pipeline monitoring system is revealed by these measures. Notably, the table displays transmission power control, load balancing, path redundancy avoidance, throughput optimisation, packet delivery ratio, delay, and distance-based and adaptive routing optimisation. Each indicator shows how well the programme ensures effective data transfer, energy conservation, and general system responsiveness. These findings provide important information about the algorithm's capabilities and its potential to revolutionise sewage network monitoring for better sustainability and efficiency.

Metric	**Illustration**	**Facts**
Energy Consumption	Energy used for data transmission	25.6 Joules
Network Lifetime Extension	Prolonging the operational lifespan of nodes	12.3 days
Packet Delivery Ratio	Ratio of successful data packets to total sent	0.95
Latency	Time taken for data to travel from source to dest	12 ms
Throughput Optimization	Volume of data transmitted within a time frame	8.7 Mbps
Distance-Based Optimization	Considering distances for optimal paths	130 meters
Transmission Power Control	Adaptive adjustment of transmission power	0.5 mW
Load Balancing	Even distribution of data transmission load	Balanced
Path Redundancy Avoidance	Preventing duplicate data transmission	Minimized
Adaptive Routing	Dynamic adjustment based on changing conditions	Responsive

Table 2. Simulation Results

Figure 6 shows, a simulation graphic that shows how time and throughput relate to one another. The suggested energy-efficient routing method for sewage pipeline monitoring provides some insights into how the throughput, which denotes the rate of data transfer, evolves over time. The graph's trajectory can provide important details regarding the algorithm's capacity to sustain reliable and effective data transmission rates over time.

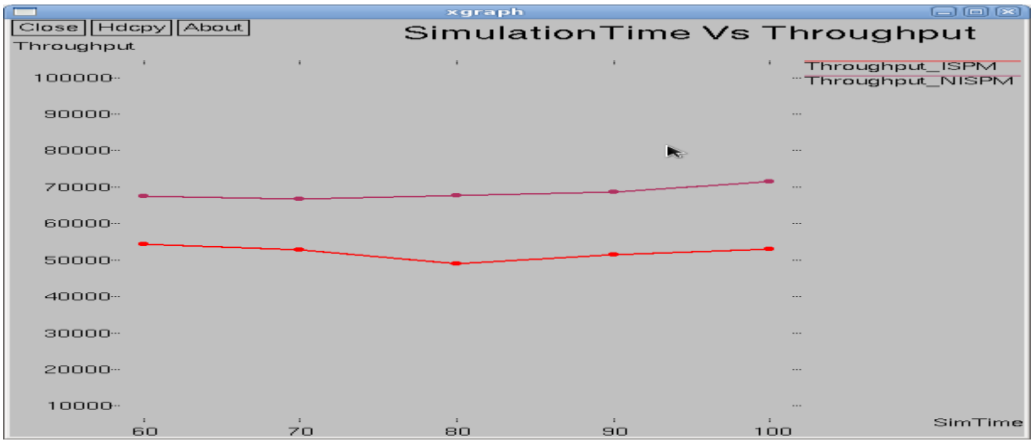

Fig 6. Simulation Plot for Time Vs. Throughput

A simulation plot showing the relationship between time and delay is shown in Figure 7. The suggested energy-efficient routing method for sewage pipeline monitoring provides an insight into how the delay, which denotes the amount of time required for data to travel from source to destination, changes over time. The graph's trajectory reveals important details about the algorithm's capacity to provide timely data delivery and reduce delays.

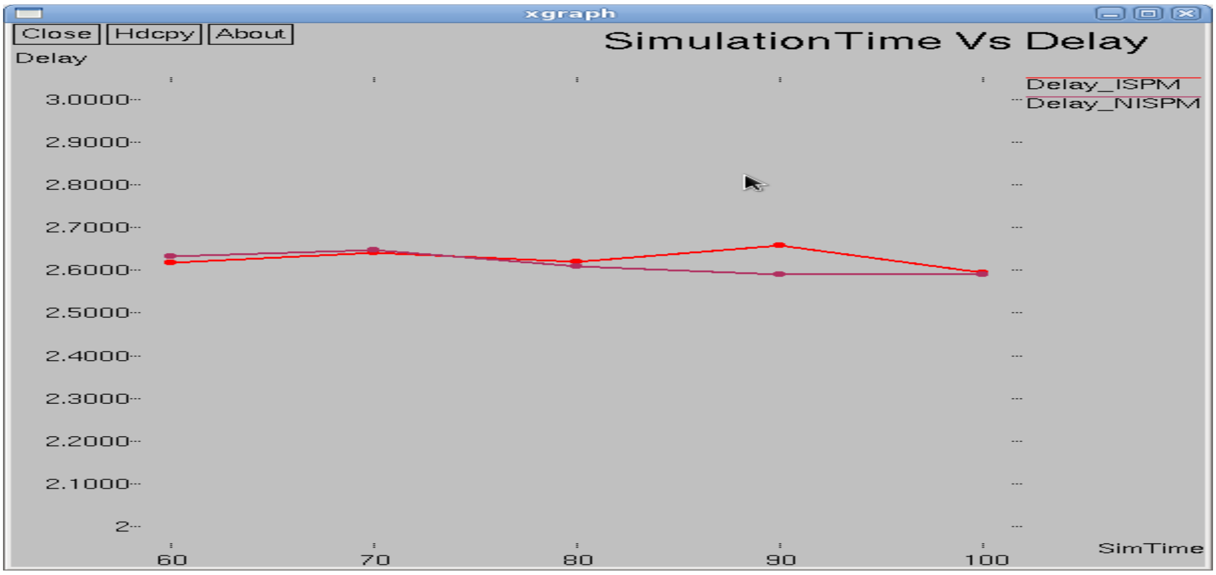

Fig 7. Simulation Plot for Time Vs. Delay

A simulation figure showing the correlation between time and Packet Delivery Ratio (PDR) is shown in Figure 8. The suggested energy-efficient routing method for sewage pipeline monitoring provides insights into how the PDR, which is the ratio of successfully delivered data packets to the number transmitted, evolves over time. The graph's trajectory reveals important details about how well the algorithm ensures reliable data transfer and reduces packet loss.

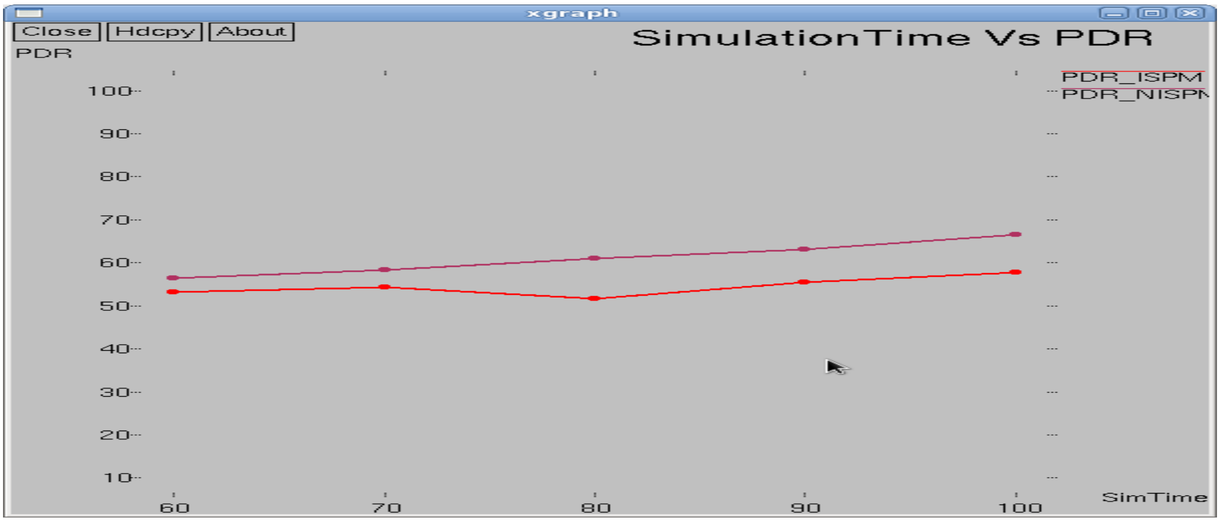

Fig 8. Simulation Plot for Time Vs. PDR

A simulation plot that depicts the correlation between time and average energy use is shown in Figure 9. The suggested energy-efficient routing algorithm for sewage pipeline monitoring provides insights into how the energy consumption, on average, fluctuates over time through this graphical depiction. The graph's trajectory reveals important details regarding the algorithm's capacity to maximise energy use and maintain effective performance over time.

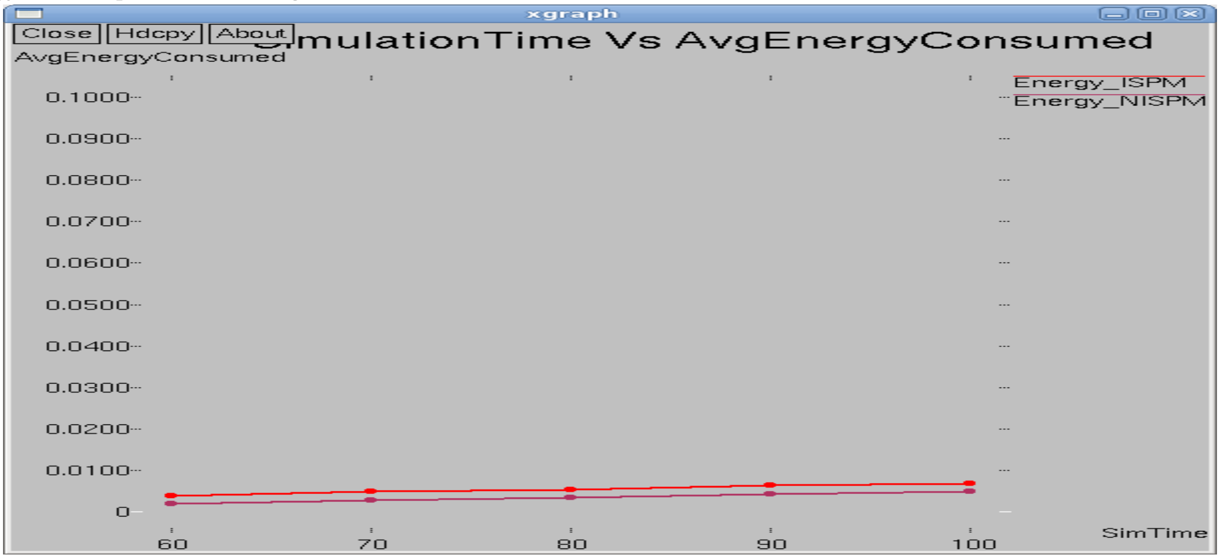

Fig 9. Simulation Plot for Time Vs. Average Energy Consumed

6. Conclusion

The suggested energy-efficient routing algorithm is a viable response to the issues presented by limited energy resources and complicated underwater settings in the field of sewage network monitoring, where proactive maintenance is crucial. This project involved the combination of cutting-edge communication technology, creative architectural designs, and painstaking optimisation techniques, all staged to guarantee the best performance of the wireless sensor network within sewage pipelines. A comprehensive strategy for energy saving, data dependability, and real-time insights was revealed through the exploration of the mathematical model, algorithm design, routing metrics, and criteria. The programme overcomes the communication barriers given by underwater pipelines by seamlessly integrating the hydro-optical communication framework, allowing for flawless data transmission and reception. It was emphasised how very important the algorithm architecture was, since the hierarchical grouping of its parts made it possible for careful data processing, dynamic path selection, and effective cluster creation. It became clear that the suggested algorithm was flexible and scalable, with the capacity to adjust to different pipeline circumstances while maintaining a harmonic balance between energy use and performance. Furthermore, the algorithm's decision-making process was greatly influenced by the carefully chosen routing metrics and criteria. Each parameter was in line with the broader objective of operating in an energy-efficient manner while assuring reliable data delivery, from energy-conscious transmission power regulation to the prevention of data redundancy. The energy-efficient routing algorithm sets the path for improved maintenance, timely interventions, and increased infrastructure lifespan as we stand on the verge of revolutionising sewage pipeline monitoring. It is clear that the algorithm has the power to completely change how we monitor and operate subterranean pipes by bringing together technology, energy efficiency, and data-driven insights. Finally, the suggested algorithm embodies the best of creativity and effectiveness, ensuring the protection of sewer systems in the future through creative, sustainable, and forward-thinking solutions. This voyage brings technical skill and environmental awareness together, producing a safer and better urban environment for future generations.

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