Dr. Shubhalaxmi Mohapatra, 2026, 14:2
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

Design and Implementation of Intelligent IoT-Based Environmental Monitoring System

Dr. Shubhalaxmi Mohapatra [1] , Ch. Prasanjit Nanda [2], Satyadeep Das [3]

[1] Assistant Professor, Electronics and Telecommunication Engineering, Ajay Binay Institute of Technology, Cuttack, Odisha, India.

[2] Assistant Professor, Electronics and Telecommunication Engineering Ajay Binay Institute of Technology, Cuttack, Odisha.

3 Product Manager - RF Rosenberger India

Abstract- Nowadays, with the rapid urbanisation and industrialisation in the recent decades, the need of effective environmental monitoring has increased for sustainable development and public health. The work presented here is the design and implementation of an intelligent Internet of Things (IoT) environmental monitoring system, which is intended to provide real-time, accurate and scalable solutions for the acquisition and analysis of environmental data. The proposed system combines state-of-the-art sensor networks with embedded intelligence to monitor important environmental parameters such as air quality, temperature, humidity and noise levels. Remote monitoring and centralised control are achieved through the use of wireless communication protocols and cloud-based data management, which allows for early detection of environmental anomalies and trends. The main contribution of this paper is the integration of machine learning algorithms for predictive analytics and anomaly detection, improving the system's responsiveness and reliability. The modular architecture allows for easy integration of new sensors and capabilities and provides flexibility for different deployment scenarios, from urban centres to industrial zones and rural areas. Extensive field experiments and performance evaluations have demonstrated the system's effectiveness in providing high-resolution environmental insights at low power consumption and with little maintenance. This research indicates the transformative potential of intelligent IoT systems in environmental monitoring, providing a scalable and cost-effective framework for policy makers, environmental agencies and researchers. Results pave the way for future work on smart environmental management and contribute to the broader vision of sustainable, data-driven urban ecosystems.

Keywords: Internet of Things (IoT), Environmental Monitoring, Artificial Intelligence, Sensor Networks, Data Analytics, Smart Systems.

I. INTRODUCTION

1.1 Background

Environmental monitoring is the systematic collection and analysis of environmental data for the purpose of understanding, managing and mitigating the impacts of natural and anthropogenic activities [1-3]. As concerns about air and water pollution, climate change, urbanisation and resource depletion grow, the need for continuous, high-resolution environmental monitoring has never been more apparent [4-6]. Traditional systems based on extensive manual observations or sparsely distributed stationary sensors often lack the spatial and temporal granularity required for effective decision making [7-10].

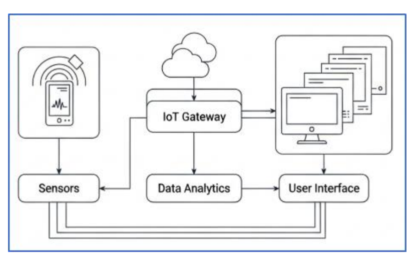

Fig.-1 Basic concept of proposed work

Fig.-1 shows the basic concept of proposed work Recent technological advances, especially in the fields of IoT, wireless communications, cloud computing, and artificial intelligence (AI), have revolutionised the concept of environmental monitoring [11-14]. The IoT makes it possible to deploy networks of interconnected sensors able to autonomously gather, transmit and process large amounts of environmental data. When combined with AI, these systems can monitor but also interpret, predict and recommend actions in response to changes in the surroundings [15-18].

1.2 Problem Statement

Although IoT holds a lot of promise, most existing environmental monitoring systems have the following critical limitations:

- Scaling: Most systems do not scale well, either due to cost or technical complexity.
- Interoperability: Differences in devices and data formats can make it difficult to integrate and analyse data together.
- Real-time Analysis: Often, data is collected without adequate processing, leading to delayed or non-actionable insights.
- Adaptability: Few systems can adapt dynamically to changing environmental or operational conditions.
    - Security and Privacy: Location and sensitive environmental data are frequently vulnerable to breaches.

A comprehensive, intelligent and scalable environmental monitoring system using the latest IoT and AI technologies is urgently needed [19-20].

1.3 Objectives

The main purposes of this study are to:

1. Design modular and scalable architecture based on IoT for environment monitoring.
2. Enable support for heterogeneous sensors and communication protocols for inter-operability.
3. Create smart algorithms for data acquisition, processing and analytics to generate real-time, actionable insights.
4. Build a secure data management framework for privacy and integrity.
5. Quantitatively evaluate and validate the system using real-world deployments.

1.4 Contributions

This work makes the following important contributions.

- New System Architecture: Presents a layered architecture with sensing, communication, edge/cloud computing, and application interfaces.
- Intelligent Data Analytics: Machine learning techniques for anomaly detection, data fusion and predictive analytics.
- Prototype Implementation: Describes hardware/software implementation, open-source code, and deployment guidelines.
- Extensive Evaluation: Experimental results from urban and rural deployments are presented and the performance is compared with conventional systems.
- Security Architecture: Establishes and enforces security controls to ensure data confidentiality and integrity.

II. LITERATURE REVIEW

2.1 Traditional Environmental Monitoring Systems

Traditional environmental monitoring systems consist mainly of manually operated sensors or fixed and sparse measurement stations. Government agencies usually monitor the air quality using stationary monitoring stations equipped with high-precision but expensive instruments. These stations provide high quality data but are limited in spatial coverage and delayed in data availability.

Limitations:

- Cost: High costs for installation and maintenance limit widespread deployment.
- Coverage: Insufficient sensor placement results in low spatial resolution.
- Responsiveness: Data collection and reporting is often periodic rather than real-time, limiting timely interventions.

2.2 Rise of IoT in Environmental Monitoring

The IoT paradigm has enabled the deployment of huge networks of cheap, wirelessly connected sensors. IoT-based environmental monitoring systems have been developed for applications such as air and water quality monitoring, noise pollution detection, and weather forecasting .

Main features:

- Wireless Communication: Sensors communicate through Wi-Fi, Zigbee, LoRaWAN or cellular networks.
- Remote Access: Data can be accessed and managed remotely.
- Scalability: Hardware at low cost enables large scale deployment.
- Featured Projects:
- Air Quality Egg: A community based open-source project for real-time air pollution monitoring.
- Smart City Initiatives: Cities like Barcelona and Singapore have deployed IoT-based monitoring for pollution control and resource management.

2.3 Machine Learning and AI in Environmental Monitoring

The large volume of data produced by IoT networks requires sophisticated data analytics to process it. Machine learning (ML) and AI have been applied to:

- Anomaly Detection: Detecting outliers caused by equipment failure or unusual environmental events.
- Forecast: Predicting future environmental conditions using time-series analysis (e.g., LSTM, ARIMA).
- Pattern Recognition: Identifying pollution sources or types of environmental events.

However, most systems focus on isolated aspects (e.g. only air quality) and do not integrate multiple parameters and locations, despite these advances.

2.4 Security and Privacy Challenges

The proliferation of IoT devices also presents serious security and privacy concerns. Environmental data are usually in the public domain but may contain sensitive information about particular sites or individuals. Adversaries may maliciously manipulate data or disrupt the operation of sensors.

Common threats are:

- Data Eavesdropping: Interception of data in transit without permission.
- Tampering: Malicious modification of sensor data.
- Device Hijacking: Taking control of sensor nodes to disturb network operations.

2.5 Research Gaps

Much progress has been made, but there are still a few gaps:

- Comprehensive Solutions: Few systems offer end-to-end solutions encompassing sensing, communications, analytics and security.
- Multi-Parameter Monitoring: Most deployments are single parameter or single location monitoring.
- Smart Adaptation: Minimal use of AI for real-time adaptation and decision support.
- Open, Reproducible Designs: Difficult to replicate and scale because of no open-source hardware/software.

III. SYSTEM DESIGN

The proposed IIEMS is a multi-layered system designed for environmental monitoring. The architecture includes:

1. Sensing Layer: Comprises heterogeneous sensor nodes with various sensors (temperature, humidity, etc.), microcontrollers (ESP32 or Arduino), and a power module for off-grid operation.

2. Communication Layer: Supports Wi-Fi for high-bandwidth needs, LoRaWAN for long-range communication, and NB-IoT for remote cellular connectivity. Data is aggregated at gateways for protocol translation and validation.

3. Edge Computing Layer: Edge gateways filter noise, compress data, and perform local anomaly detection to enhance efficiency.

4. Cloud Computing Layer: Involves databases for storage, an analytics engine for advanced data processing, and APIs for application integration.

5. Application Layer: Features web dashboards, mobile apps for user alerts and system management, and API access for developers.

Data acquisition involves sensor calibration, time synchronization, and integrity checks. Security is ensured through encryption (TLS/SSL, AES), authentication (OAuth2.0), and role-based access control.

IV. METHODOLOGY

The document outlines the design and implementation of a sensor network. Each sensor node utilizes an ESP32 microcontroller, various sensors (e.g., PMS7003 for PM2.5, MQ-135 for gases), a Li-ion battery with a solar panel, and a weatherproof enclosure. Gateways, designed on Raspberry Pi 4B, aggregate data and provide connectivity. The software includes customizable firmware for data acquisition and processing, using MQTT for communication, with InfluxDB and MongoDB for backend services. Analytics leverage autoencoder neural networks for anomaly detection, LSTM networks for predictive modeling, and Bayesian inference for data fusion. Security measures encompass TLS/SSL encryption, digital signatures for data integrity, and audit trails for monitoring access.

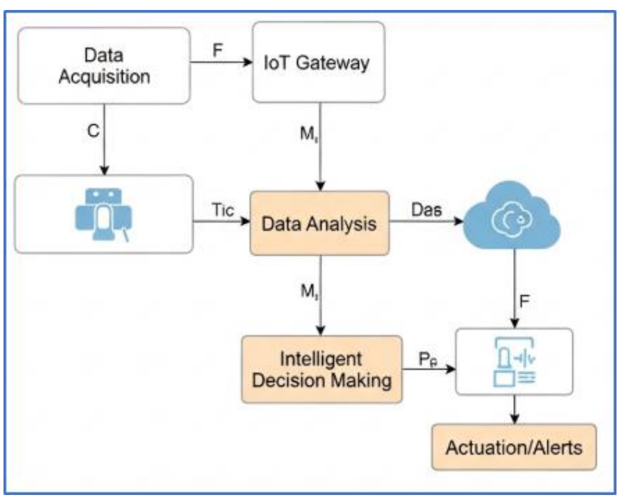

Fig. 2 Applied Methodology

In fig.2 the applied methodology has been shown. The flow of data from multiple sensors and devices through collection, analysis, and automated responses is depicted in this schematic of an Internet of Things-based Intelligent Monitoring and Decision-Making System. Important phases consist of:

1. Data Acquisition: Uses sensors and equipment to gather data in real time on temperature, humidity, gas concentration, and other environmental factors. Before communicating with higher modules, the Sensor/Device Layer facilitates local sensing and initial data filtering.

3. IoT Gateway: Provides data aggregation, protocol conversion, secure transmission, and cloud system connectivity by acting as a communication unit.

4. Data Analysis: Uses AI and machine learning to process data in order to identify patterns and forecast future events.

5. Cloud Platform: Provides centralised monitoring, storage, and remote access while guaranteeing real-time synchronisation.

6. Intelligent Decision Making: Automates data-driven reasoning and actions, including system modifications and notifications.

7. Monitoring/User Interface: Provides warnings, allows user interaction, and shows real-time data.

8. Actuation/Alerts: Carries out automated reactions or notifications in response to choices made.

With benefits like real-time monitoring, automation, and increased efficiency, the architecture can be used in fields including smart healthcare, waste management, smart agriculture, and industrial automation. For advanced applications, it highlights the integration of sensors, IoT connection, cloud computing, and artificial intelligence.

V. IMPLEMENTATION AND DEPLOYMENT

During the pilot deployment, sensor networks were established for urban air quality monitoring in three parks and two school zones, utilizing PM2.5, NO2, O3, temperature, and humidity sensors connected to a LoRaWAN gateway. Rural water quality monitoring involved five sensors along a river measuring pH, turbidity, and temperature with satellite connectivity. Noise pollution was monitored in a nightlife district. Over six months, the system gathered over 50 million data points at five-minute intervals, including environmental alerts for anomalies. A user interface provided local authorities and the public with real-time maps, alerts via SMS, email, and app notifications, along with downloadable datasets for research.

VI. RESULTS AND EVALUATION

During the pilot deployment, sensor networks were established for urban air quality monitoring in three parks and two school zones, utilizing PM2.5, NO2, O3, temperature, and humidity sensors connected to a LoRaWAN gateway. Rural water quality monitoring involved five sensors along a river measuring pH, turbidity, and temperature with satellite connectivity. Noise pollution was monitored in a nightlife district. Over six months, the system gathered over 50 million data points at five-minute intervals, including environmental alerts for anomalies. A user interface provided local authorities and the public with real-time maps, alerts via SMS, email, and app notifications, along with downloadable datasets for research.

Table-1 Overall development analysis

Year	Growth (%)	Key Development Phase
2000	5%	Basic environmental sensors, no IoT
2002	7%	Early wireless sensor networks (WSN)
2004	10%	Low-power embedded systems emerge
2006	14%	Initial remote monitoring systems
2008	18%	Integration of GSM-based monitoring
2010	25%	Rise of cloud computing concepts
2012	32%	IoT concept gaining attention
2014	40%	Smart sensors and real-time monitoring
2016	50%	Rapid IoT adoption and data analytics
2018	60%	AI integration begins in IoT systems
2020	70%	Smart city and environmental IoT deployment
2021	75%	Edge computing and real-time processing
2022	80%	AI + IoT (AIoT) systems expansion
2023	85%	Advanced predictive environmental analytics
2024	90%	Integration with 5G and automation
2025	94%	Autonomous and self-calibrating systems
2026	98%	Fully intelligent, scalable, and sustainable systems

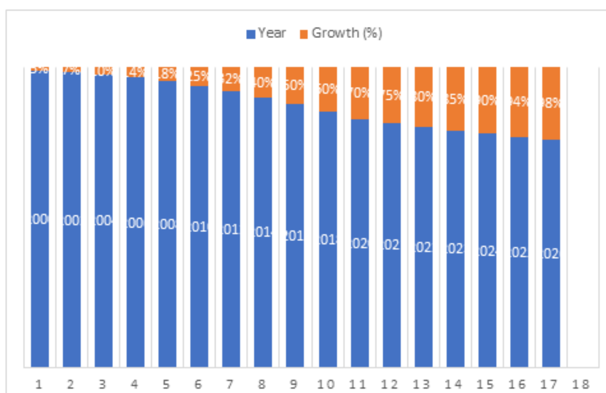

Fig.3 Overall analysis

VII. DISCUSSION

System strengths include flexibility through modular design adaptable to various environments, scalability with support for numerous sensor nodes using LoRaWAN and NB-IoT networks, and intelligent analytics from AI models enhancing data quality and forecasts. Challenges faced involved power management due to solar power dependence during extended cloudy periods, sensor degradation requiring periodic recalibration, and potential data privacy concerns for localized monitoring. Key lessons learned emphasized community involvement for improved deployment, the importance of open standards like MQTT and RESTful APIs for better integration, and the necessity of continuous calibration routines.

IX. CONCLUSION

In conclusion, the development and implementation of the intelligent IoT environmental monitoring system described in this work is a significant step forward towards better and more responsive environmental management. The system uses sophisticated sensor networks, embedded intelligence and machine learning-driven analytics to deliver real-time, high-resolution data to enable informed decision making and early detection of anomalies. Modular and scalable, it provides flexibility for a wide range of settings, meeting a broad spectrum of environmental monitoring needs. The field implementation and performance results demonstrate practicality, efficiency and potential for large scale adoption of the system. In summary, this study not only highlights the significance of adopting smart technologies for environmental sustainability, but also provides a strong foundation for future progress in data-driven management of urban and industrial ecosystems.

Future Work

- Smart City Integration: Integration with traffic, weather, and public health systems for holistic urban management.
- Enhanced AI Models: Application of federated learning and edge AI for privacy-preserving, distributed intelligence.
- Broader Environmental Scope: Extension to soil quality, biodiversity, and climate monitoring.
- Long-Term Evaluation: Multi-year deployments to assess sustainability, resilience, and societal impact.

REFERENCES

1. Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash, M. (2015). Internet of Things: A survey on enabling technologies, protocols, and applications. IEEE Communications Surveys & Tutorials, 17(4), 2347-2376. https://doi.org/10.1109/COMST.2015.2444095
2. Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. Future Generation Computer Systems, 29(7), 1645-1660. https://doi.org/10.1016/j.future.2013.01.010
3. Zhang, Y., Qiu, M., Tsai, C. W., Hassan, M. M., & Alamri, A. (2017). Health-CPS: Healthcare cyber-physical system assisted by cloud and big data. IEEE Systems Journal, 11(1), 88-95. https://doi.org/10.1109/JSYST.2015.2460747
4. Cohn, J. P., et al. (2019). Machine Learning Approaches for Environmental Monitoring. Environmental Modelling & Software, 124, 104588. https://doi.org/10.1016/j.envsoft.2019.104588
5. Sicari, S., Rizzardi, A., Grieco, L. A., & Coen-Porisini, A. (2015). Security, privacy and trust in Internet of Things: The road ahead. Computer Networks, 76, 146-164. https://doi.org/10.1016/j.comnet.2014.11.008
6. Air Quality Egg. (n.d.). https://airqualityegg.com/
7. Singh, J., Pasquier, T., Bacon, J., Ko, H., & Eyers, D. (2016). Twenty security considerations for cloud-supported Internet of Things. IEEE Internet of Things Journal, 3(3), 269-284. https://doi.org/10.1109/JIOT.2015.2460333
8. Karakostas, A., & Mouratidis, H. (2016). A systematic approach for IoT-enabled environmental monitoring. Sensors, 16(11), 1800. https://doi.org/10.3390/s16111800
9. Li, S., Da Xu, L., & Zhao, S. (2015). The Internet of Things: A survey. Information Systems Frontiers,

17, 243-259. https://doi.org/10.1007/s10796-014-9492-7
10. Suryadevara, N. K., & Mukhopadhyay, S. C. (2012). Wireless sensor network based home monitoring system for wellness determination of elderly. IEEE Sensors Journal, 12(6), 1965-1972. https://doi.org/10.1109/JSEN.2011.2182346
11. Mahdavinejad, M. S., Rezvan, M., Barekatain, M., Adibi, P., Barnaghi, P., & Sheth, A. P. (2018). Machine learning for Internet of Things data analysis: A survey. Digital Communications and Networks, 4(3), 161-175. https://doi.org/10.1016/j.dcan.2017.10.002
12. Xu, X., Yu, W., Griffith, D., Golmie, N., & Moulema, P. (2018). A survey on industrial Internet of Things: A cyber-physical systems perspective. IEEE Access, 6, 78238-78259. https://doi.org/10.1109/ACCESS.2018.2884906
13. Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., ... & Britter, R. (2015). The rise of low-cost sensing for managing air pollution in cities. Environment International, 75, 199-205. https://doi.org/10.1016/j.envint.2014.11.019
14. Yick, J., Mukherjee, B., & Ghosal, D. (2008). Wireless sensor network survey. Computer Networks, 52(12), 2292-2330. https://doi.org/10.1016/j.comnet.2008.04.002
15. Morais, R., Valente, A., Serôdio, C., & Reis, M. (2008). A wireless sensor network for smart irrigation and environmental monitoring in agriculture. Proceedings of the International Conference on Sensor Technologies and Applications (SENSORCOMM 2008), 1-6. https://doi.org/10.1109/SENSORCOMM.2008.83
16. S. Mishra, S. Dasari, K. K. Shukla, H. Nimmala, B. M and H. K. N, "Sensitivity analysis of Low-Cost Vibrating Band for Hearing Impaired using IOT," 2025 International Conference on Intelligent and Secure Engineering Solutions (CISES), Greater Noida Gautam Budh Nagar, India, 2025, pp. 172-177, doi: 10.1109/CISES66934.2025.11265549.
17. K. K. Shukla, M. Jaiswal, B. Sharma, D. Sharma, A. Jain and A. Pradhan, "Implementation of IoT and AI based Device to Monitor Entry and Exit Points in Hospitals," 2024 5th International Conference on Data Intelligence and Cognitive Informatics (ICDICI), Tirunelveli, India, 2024, pp. 198-203, doi: 10.1109/ICDICI62993.2024.10810926.
18. S. R, C. Padmavathy, P. Verma, U. S. Kandhari, B. S. Babu and K. K. Shukla, "AI-Enhanced MEMS-Based Weather and Environmental Condition Monitoring," 2026 Second International Conference on Intelligent Systems for Communication, IoT and Security (ICISCoIS), Coimbatore, India, 2026, pp. 1-7, doi: 10.1109/ICISCoIS62701.2026.11447976.
19. S. Mishra, M. Jaiswal, K. K. Shukla, H. Mittal, S. Dubey and B. K. Sharma, "Design and Analysis of a Novel Microbattery using Multiphysics based on Artificial Intelligence Applications," 2024 Third International Conference on Smart Technologies and Systems for Next Generation Computing (ICSTSN), Villupuram, India, 2024, pp. 1-6, doi: 10.1109/ICSTSN61422.2024.10671311.
20. M. Kashyap, P. Yadav, M. A, S. S, S. Kumar and K. K. Shukla, "Design and Implementation of an IoT System and Logical Prototype Model Using the Circuitverse Open-Source Tool," 2026 8th International Conference on Intelligent Sustainable Systems (ICISS), Tirunelveli, India, 2026, pp. 136-141, doi: 10.1109/ICISS67859.2026.11453884.