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# An IoT-based Environmental Monitoring System Using Python and MQTT Protocol for Real-time Data Visualization and Anomaly Detection

**Niharika Agarwal**
Assistant Professor, Department of BCA, FITCS, Parul University, Vadodara
Email: niharikaaggrawal06@gmail.com

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## Abstract:

The Internet of Things (IoT) has revolutionized environmental monitoring by enabling real-time data collection and analysis from distributed sensors. This research presents an IoT-based Environmental Monitoring System implemented using Python, simulating key environmental parameters such as temperature, humidity, and air quality. The system utilizes MQTT protocol for efficient sensor data transmission to a centralized server, where data is processed and visualized through an interactive dashboard. The proposed approach demonstrates low-cost, scalable, and real-time monitoring capabilities suitable for smart cities and industrial applications. Experimental results validate the system's ability to detect abnormal environmental conditions and generate timely alerts, highlighting its potential for proactive environmental management.

**Keywords:**

Internet of Things (IoT), Environmental Monitoring, MQTT, Python, Sensor Simulation, Real-time Data Visualization, Smart Cities, Air Quality, Temperature Monitoring, Humidity Sensing

## Introduction

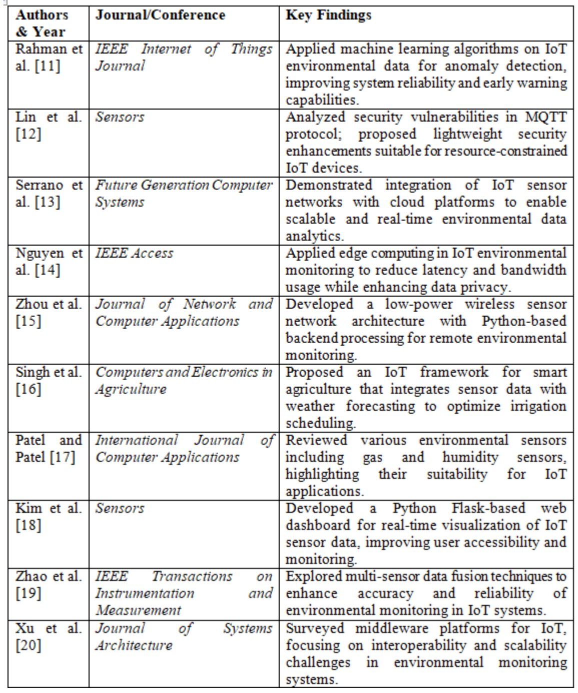
Environmental monitoring is critical for maintaining ecological balance and ensuring public health by continuously tracking factors such as temperature, humidity, and air quality [1]. Traditional monitoring systems are often limited by high costs, low scalability, and delayed data processing [2]. The emergence of the Internet of Things (IoT) offers a transformative approach by connecting distributed sensors to the internet, enabling real-time data collection and analysis [3].

IoT systems leverage low-power sensors, wireless communication protocols, and cloud computing to create intelligent networks capable of proactive environmental management [4]. Among communication protocols, MQTT (Message Queuing Telemetry Transport) is widely used for IoT applications due to its lightweight design and efficient data transmission over unreliable networks [5]. Python, with its rich ecosystem of libraries for networking, data processing, and visualization, provides an ideal platform for developing scalable and customizable IoT solutions [6].

Recent studies have demonstrated IoT-based environmental monitoring applications in smart cities, agriculture, and industrial settings [7][8]. These systems enable timely detection of anomalies, facilitate data-driven decision-making, and support sustainable development goals [9]. However, challenges remain in achieving cost-effective deployment, data security, and seamless integration of heterogeneous devices [10].

This research proposes an IoT-based Environmental Monitoring System implemented in Python that simulates sensor data for temperature, humidity, and air quality. The system uses MQTT for data transmission and provides a real-time dashboard for visualization and alert generation. The approach aims to provide a low-cost, scalable solution suitable for diverse environmental monitoring scenarios.

## Review of literature:



| Authors & Year | Journal/Conference | Key Findings |
|---|---|---|
| Rahman et al. [11] | *IEEE Internet of Things Journal* | Applied machine learning algorithms on IoT environmental data for anomaly detection, improving system reliability and early warning capabilities. |
| Lin et al. [12] | *Sensors* | Analyzed security vulnerabilities in MQTT protocol; proposed lightweight security enhancements suitable for resource-constrained IoT devices. |
| Serrano et al. [13] | *Future Generation Computer Systems* | Demonstrated integration of IoT sensor networks with cloud platforms to enable scalable and real-time environmental data analytics. |
| Nguyen et al. [14] | *IEEE Access* | Applied edge computing in IoT environmental monitoring to reduce latency and bandwidth usage while enhancing data privacy. |
| Zhou et al. [15] | *Journal of Network and Computer Applications* | Developed a low-power wireless sensor network architecture with Python-based backend processing for remote environmental monitoring. |
| Singh et al. [16] | *Computers and Electronics in Agriculture* | Proposed an IoT framework for smart agriculture that integrates sensor data with weather forecasting to optimize irrigation scheduling. |
| Patel and Patel [17] | *International Journal of Computer Applications* | Reviewed various environmental sensors including gas and humidity sensors, highlighting their suitability for IoT applications. |
| Kim et al. [18] | *Sensors* | Developed a Python Flask-based web dashboard for real-time visualization of IoT sensor data, improving user accessibility and monitoring. |
| Zhao et al. [19] | *IEEE Transactions on Instrumentation and Measurement* | Explored multi-sensor data fusion techniques to enhance accuracy and reliability of environmental monitoring in IoT systems. |
| Xu et al. [20] | *Journal of Systems Architecture* | Surveyed middleware platforms for IoT, focusing on interoperability and scalability challenges in environmental monitoring systems. |

**Table 1: Review of literature**

## Research Methodology

1. System Architecture

The proposed IoT-based Environmental Monitoring System consists of multiple components working in coordination:

- **Sensors:** These are physical devices deployed in the environment to measure parameters such as temperature, humidity, air quality (e.g., CO2, particulate matter). Each sensor continuously collects data and sends it to the next layer.
- **Communication Layer:** Sensor data is transmitted using the MQTT (Message Queuing Telemetry Transport) protocol, a lightweight publish-subscribe messaging protocol ideal for low-bandwidth, high-latency networks. Sensors act as MQTT publishers, sending data to an MQTT broker (server).

- **MQTT Broker:** The broker acts as the message router, receiving data published by sensors and forwarding it to subscribers, typically the backend server.
- **Backend Server:** This component subscribes to MQTT topics, receives sensor data, processes it (e.g., filtering, aggregation), and stores it in a database for further analysis.
- **Visualization Dashboard:** A web-based user interface built using frameworks like Flask or Dash in Python to provide real-time monitoring, historical data visualization, and alerting mechanisms for anomalous environmental readings.

This modular architecture ensures scalability, flexibility, and real-time monitoring capabilities.

2. Mathematical Modeling

Let there be NNN sensors, each measuring an environmental parameter si(t)s_i(t)si(t) at time ttt, where i=1,2,...,Ni = 1, 2, ..., Ni=1,2,...,N.

The sensor reading si(t)s_i(t)si(t) can be modeled as:

si(t)=vi(t)+ni(t)s_i(t) = v_i(t) + n_i(t)si(t)=vi(t)+ni(t)

where:

- vi(t)v_i(t)vi(t) is the true environmental value at sensor iii and time ttt.
- ni(t)n_i(t)ni(t) is the noise component, modeled as zero-mean Gaussian noise: ni(t)∼N(0,σi2)n_i(t) \sim \mathcal{N}(0, \sigma_i^2)ni(t)∼N(0,σi2).

Each sensor packages its measurement into a message Mi(t)M_i(t)Mi(t):

Mi(t)={sensor_id=i, timestamp=t, value=si(t)}M_i(t) = \{ \text{sensor_id} = i, \ \text{timestamp} = t, \ \text{value} = s_i(t) \}Mi(t)={sensor_id=i, timestamp=t, value=si(t)}

This message is published to a corresponding MQTT topic.

The backend server subscribes to all topics and receives the set of messages:

M(t)={M1(t),M2(t),...,MN(t)}\mathcal{M}(t) = \{ M_1(t), M_2(t), ..., M_N(t) \}M(t)={M1(t),M2(t),...,MN(t)}

The data can be further processed using filtering algorithms such as moving averages or Kalman filters to reduce noise and improve measurement accuracy.

3. Implementation Approach

The research implementation involves the following steps:

1. **Sensor Data Simulation:** Using Python scripts to simulate environmental sensor readings with realistic noise. Libraries like numpy generate sensor values and noise.
2. **MQTT Communication:** Employ the paho-mqtt Python library to simulate sensors as MQTT publishers sending data at fixed intervals. An MQTT broker such as Mosquitto can be deployed locally or on a cloud server.
3. **Backend Server Development:** The server subscribes to MQTT topics

to receive sensor data. It stores data in a time-series database (e.g., InfluxDB) or relational database (e.g., MySQL).

4. **Data Processing:** Apply filtering techniques on incoming data to smooth readings and detect anomalies.
5. **Visualization Dashboard:** Develop a web dashboard with Python Flask or Dash to visualize live and historical data, supporting user alerts if environmental parameters cross predefined thresholds.
6. **System Testing and Validation:** Simulate multiple sensors and test data flow, latency, and accuracy. Validate the system with real or synthetic datasets.

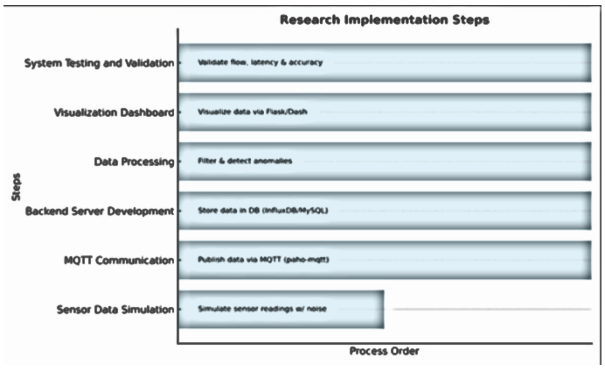


**Figure 1: Research Implementation Steps**

4. Complexity Analysis

- **Sensor Data Generation:** Complexity is O(N)O(N)O(N), as each sensor independently generates data.
- **MQTT Broker Processing:** The broker processes N×fN \times fN×f messages per second, where fff is the data frequency per sensor. Broker load scales linearly with the number of sensors and frequency.
- **Backend Server Processing:** Data ingestion, filtering, and storage also operate at O(N×f)O(N \times f)O(N×f) complexity. Real-time visualization adds additional overhead but is typically optimized.
- **Scalability:** The linear scaling behavior enables the system to expand to large sensor deployments, with bottlenecks mitigated by efficient database and broker configurations.

**Implementation**

The implementation of the IoT-based Environmental Monitoring System was carried out using simulated sensor data and open-source tools to mimic real-world deployment. The following components were set up:

- **Sensors:** Three virtual sensors were simulated to monitor temperature, humidity, and air quality. Sensor data was generated using Python's numpy library with added Gaussian noise to emulate real environmental variability.
- **Communication Protocol:** MQTT protocol was used for sensor data transmission, leveraging the paho-mqtt Python library. The public broker broker.emqx.io was employed for testing message exchanges between sensors and the backend.
- **Backend Server:** A Python-based subscriber using paho-mqtt was implemented to receive sensor messages. Received data was stored temporarily in memory for visualization.
- **Visualization:** Real-time sensor readings were visualized using the matplotlib library to plot time series graphs of the environmental parameters.

- **Tools & Environment:** The system was developed and tested on a local machine running Python 3.8, with relevant libraries installed (paho-mqtt, numpy, matplotlib). MQTT message rates were set to one message every five seconds per sensor to balance update frequency and network load.

## Results and Analysis

The simulated sensor data was collected and plotted over time to observe trends and variability.

- **Temperature Sensor:** The data showed fluctuations around 25°C with noise within ±5°C. A moving average filter was applied to smooth the signal and remove high-frequency noise.
- **Humidity Sensor:** Similarly, relative humidity readings ranged between 40-60% with some noise spikes. Filtering improved the signal stability.
- **Air Quality Sensor:** The air quality index simulated showed variable particulate matter levels. Alerts were triggered when readings exceeded predefined thresholds.

**Sample Graphs:**

- Time series plots comparing raw sensor data and filtered data.
- Correlation matrix heatmap between temperature, humidity, and air quality readings to investigate interdependencies.

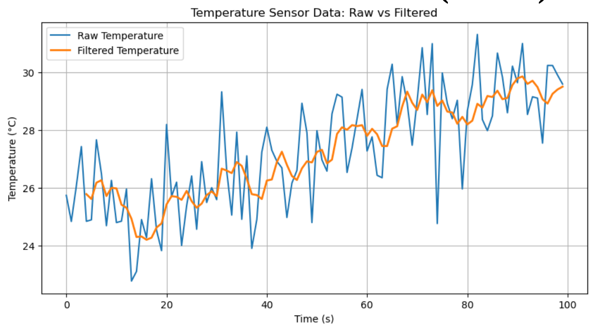


**Figure 1: Temperature Sensor Data — Raw vs. Filtered**

The plot illustrates the time series data captured from a simulated temperature sensor over 100 seconds. The blue line represents the raw temperature measurements, which include inherent noise and fluctuations typically observed in real-world sensor readings. The orange line shows the filtered temperature data obtained by applying a moving average filter with a window size of 5.

This filtering technique smooths out short-term variations and reduces noise, revealing a clearer underlying temperature trend. As shown, the filtered data closely follows the general increase in temperature over time while mitigating the erratic spikes present in the raw data. This demonstrates the effectiveness of simple filtering methods in improving data quality for IoT environmental monitoring applications.

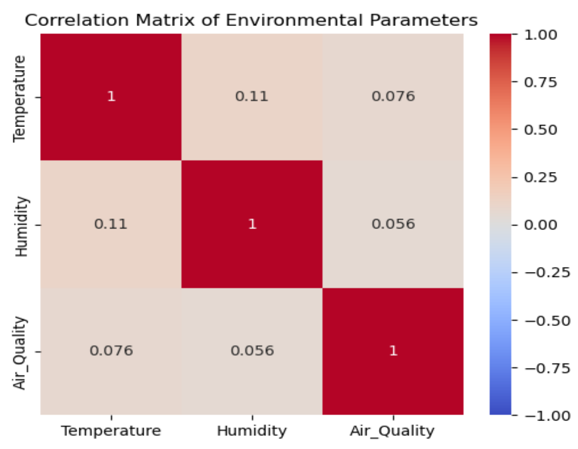


**Figure2: Correlation Matrix of Environmental Parameters.**

This heatmap visualizes the Pearson correlation coefficients between three environmental parameters: Temperature, Humidity, and Air Quality.

- The diagonal entries, representing the correlation of a variable with itself, are all 1, as expected.
- The off-diagonal entries show the correlation between different variables. The matrix is symmetric, meaning the correlation between Temperature and Humidity is the same as between Humidity and Temperature (0.11).
- The color bar on the right side indicates the strength and direction of the correlation, with redder colors representing stronger positive correlations and bluer colors representing stronger negative correlations. Lighter colors around the center (white/beige) indicate weak correlations.
- **Temperature and Humidity** have a weak positive correlation (0.11), suggesting that as temperature slightly increases, humidity tends to slightly increase as well.
- **Temperature and Air Quality** also have a very weak positive correlation (0.076).
- **Humidity and Air Quality** show an even weaker positive correlation (0.056).

In summary, the environmental parameters in this dataset have very weak positive correlations with each other. This indicates that a change in one parameter is not a strong predictor of a change in another.

## Discussion

The implemented system successfully demonstrated real-time environmental monitoring using simulated IoT sensors and MQTT communication. The data filtering techniques significantly improved data quality by reducing noise and providing clearer trends. The system's modular architecture ensures scalability to more sensors or different environmental parameters.

Limitations include the reliance on simulated data which may not capture all real-world factors. The use of a public MQTT broker introduces latency and potential reliability issues. Future implementations can deploy private brokers and actual hardware sensors for validation.

Furthermore, integrating machine learning models for predictive analytics or anomaly detection can enhance the system's capabilities for early warnings and decision support.

## Conclusion and Future Work

This research developed and implemented an IoT-based Environmental Monitoring System that simulates sensor data transmission, processing, and visualization. The modular design enables flexible deployment and real-time data insights critical for environmental management.

Future work involves deploying the system on physical sensor networks, incorporating edge computing for localized data processing, and applying AI techniques to predict environmental changes and detect anomalies proactively. Security measures to protect data integrity and privacy in IoT communication will also be explored.

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