engineering proceedings

MDPI

Proceeding Paper

Prototyping LoRaWAN-Based Mobile Air Quality Monitoring System for Public Health and Safety †

Tanzila [1], Sundus Ali [1,*], Muhammad Imran Aslam [1], Irfan Ahmed [2] and Ayesha Ahmed [3]

[1] Department of Telecommunications Engineering, NED University of Engineering and Technology, Karachi 75270, Pakistan; tanzila4330160@cloud.neduet.edu.pk (T.); iaslam@neduet.edu.pk (M.I.A.)
[2] Department of Physics, NED University of Engineering and Technology, Karachi 75270, Pakistan; irfans@neduet.edu.pk
[3] Department of Computer Science and Information Technology, NED University of Engineering and Technology, Karachi 75270, Pakistan; ayesha.ahmed2389@gmail.com
* Correspondence: sundus@neduet.edu.pk

† Presented at the 12th International Electronic Conference on Sensors and Applications (ECSA-12), 12–14 November 2025; Available online: https://sciforum.net/event/ECSA-12.

Abstract

In this paper, we have presented the design, prototyping and working of a cost-effective, energy-efficient, and scalable air quality monitoring system (AQMS), enabled by Low power, long Range Wide Area Network (LoRaWAN), an Internet of Things (IoT) technology designed to provide connectivity for massive machine type communication applications. The growing threat of air pollution necessitates outdoor and mobile environmental monitoring systems to provide real-time, location-specific data, which are unfortunately not possible with fixed monitoring devices. For our AQMS, we have developed two custom-built sensor nodes. First node is equipped with Nucleo-WL55JC1 microcontroller and sensors to measure temperature, humidity, and carbon dioxide (CO_2), while other node is equipped with Arduino MKR WAN 1310 controller with sensors to measure carbon monoxide (CO), ammonia (NH_3), and particulate matter (PM2.5 and PM10). These sensor nodes connect to a WisGate Edge LoRaWAN gateway, which aggregates and forwards the sensor data to The Things Network (TTN) for processing and cloud storage. The final visualization is handled via the Ubidots IoT platform, allowing for real-time visualization of environmental data. Besides environmental data, we were able to acquire received signal strength indicator, signal-to-noise ratio as well as frame counter which shows the number of packets received by the gateway. We performed laboratory testing, which confirmed reliable communication, with a packet delivery rate of 98% and minimal average latency of 2.5 seconds. Both nodes operated efficiently on battery power, with the Nucleo-WL55JC1 consuming an average of 20 mA in active mode, while the Arduino MKR WAN 1310 operated at 15 mA. These values ensured extended operation for remote deployment. The system's low power consumption and modular architecture make it viable for smart city applications and large-scale deployments in resource-constrained areas.

Keywords: sensors; LoRaWAN; air quality; internet of things; mobile; public health

Academic Editor(s): Name

Published: date

Citation: Tanzila; Ali, S.; Aslam, M.I.; Ahmed, I.; Ahmed, A. Prototyping LoRaWAN-Based Mobile Air Quality Monitoring System for Public Health and Safety. *Eng. Proc.* **2025**, *volume number*, x. https://doi.org/10.3390/xxxxx

1. Introduction

Environmental monitoring plays a vital role in addressing the growing concerns related to climate change, air pollution, and declining air quality. The rapid pace of industrialization, urban expansion, and agricultural practices has significantly contributed to the emission of harmful pollutants [1]. These pollutants pose serious threats to public health, ecological balance, and climate stability. Therefore, continuous and real-time monitoring of environmental parameters is essential for effective risk mitigation and the promotion of sustainable development [2]. Conventional air quality monitoring systems (AQMSs) are often cost-prohibitive, require intensive maintenance, and lack scalability, especially in remote or large-scale outdoor environments. Furthermore, solutions based on WiFi-enabled technologies have coverage limitations and are highly dependent on reliable internet connectivity, making them unsuitable for mobile or distributed deployments.

AQMSs have evolved significantly from traditional offline methods to modern IoT-based solutions. Early offline systems relied on manual sampling and laboratory analysis using techniques like gravimetric analysis [1] and gas chromatography [3], which provided accurate data but suffered from time delays and high costs. Subsequent online systems introduced real-time monitoring through wired or cellular networks [4], though they remained limited by power requirements and infrastructure costs [5]. The advent of IoT-based monitoring systems has revolutionized the field by combining wireless communication, low-cost sensors, and cloud computing [6-8]. These systems typically consist of sensor nodes, gateways, network servers, and visualization dashboards. Among wireless technologies, LoRaWAN has emerged as particularly suitable for environmental monitoring due to its long-range capability, low power consumption, and robust performance in challenging conditions [9,10]. The protocol's star-of-stars topology, AES-128 encryption, and adaptive data rate features enable secure, scalable deployments with packet delivery rates exceeding 98% [9,10]. These developments have made LoRaWAN- based systems increasingly viable for both urban and remote environmental monitoring applications.

In this paper, we have presented an end-to-end, multi-node LoRaWAN-based AQMS capable of sensing critical air quality parameters. By utilizing LoRaWAN, the system ensures remote, reliable, real-time data acquisition from the two sensor nodes developed by us, which are deployed in various environments. The data is collected, transmitted, and visualized through a cloud-connected Ubidots dashboard designed for continuous monitoring. This indigenously developed solution offers a proactive approach to public health and safety through timely alerts, early warnings, and insightful trend analysis.

The structure of the paper is as follows: In Section 2, we have discussed the current state-of-the-art in the domain of LoRaWAN based AQMS. In Section 3, we have outlined our proposed LoRaWAN based AQMS system and in section 4 discussed in detail the system design implementation. Section 5 presents the results and discussion on the said results while Section 6 concludes the paper.

2. Literature Review

In this section, we have discussed some recent work conducted in development of AQMS using LoRaWAN as an IoT technology. The authors in [11] have presented an outdoor LoRaWAN based AQMS node designed to collect CO_2, CO, NO_2, SO_2, and $PM_{2.5}$, along with temperature and humidity using Arduino UNO and LoRa shield, connected via The Things Network (TTN) gateway to The Things Network. Limitation includes lack of calibration accuracy, no actuator/control mechanisms, and reliance on TTN, which may limit scalability or security. In [12], the authors have presented a system where a lightweight UAV-mounted LoRaWAN node was used to carry gas sensors suite measuring CO, NO_2, NH_3, SO_2, PM_{10} and $PM_{2.5}$. It uses a Teensy 4.0 microcontroller and an end device LoRa module configured to communicate with a gateway via RA 01 module. The work adds mobility and flexibility to conventional fixed monitoring via UAV deployment, but on the other hand UAV flight duration constraints; limited coverage area per flight and no integration with real time actuators limits the work presented in this paper. In [13], the authors have proposed a Wireless Sensor and Actuator Network (WSAN) AQMS with both indoor and outdoor clusters. Indoor nodes sense temperature, humidity, and dust (PM), while outdoor nodes are waterproof and solar powered. Sensor data is sent on uplink to a Dragino LoRa gateway, and downlink controls actuators (e.g. negative ion generators) to improve air quality. Cloud platform uses TTN and TagoIO dashboard [14]. The system combines monitoring with actuators for proactive air quality improvement; real operational feedback loop. The authors in [15] have developed a system which employs environmental sensor modules (CO_2, PM, humidity/temperature) paired with an ESP32 based LoRaWAN/GPRS module. Integrated automation triggers threshold based actions (e.g. ventilation), with cloud visualization. Primary focus of this work is on indoor passenger safety (e.g. vehicles or cabins), real time actuation, and multiple gas/particulate detection. In [16], the authors introduce low-cost particulate and gas sensors with LoRaWAN connectivity and a machine learning based calibration method to improve accuracy. Although they have provided significant ML based sensor calibration analysis, the work does not provide details onto LoRaWAN based data communication, in fact they have employed WiFi as a mean to collect sensor data. Table 1 summarizes these investigations as well as highlights features of our proposed system which is the focus of this paper.

Table 1. Summary of literature review.

Work	Pollutants	Controller	Gateway	Contributions	Limitations
LoRaWAN IoT AQMS for long range outdoor monitoring [11]	NO_2, SO_2, CO_2, CO, PM, temperature, humidity	Arduino Uno and LoRa Shield	Dragino	portable, Solar-powered, Real-time data on ThingSpeak GUI	Delay of 10s in data transmission; Lack of prediction techniques
Remote AQM Using UAV and LoRaWAN [12]	CO, NO_2, NH_3, SO_2, PM	Teensy 4.0 development board	ESP32 board + RA01 LoRa module	Adds aerial mobility to monitoring; compact and low power UAV node	UAV flight-time limits; limited area per mission; lacks real-time control
Wireless sensor and actuator network (WSAN) for AQMS using LoRa [13]	PM, CO, LPG, CH_4, temperature, humidity	Heltec LoRa32 module (indoor); ATmega328P (outdoor)	Dragino	Active air quality improvement via actuators; Web/smartphone monitoring; Low packet loss (<0.1%).	Actuation limited in scale; dust monitoring only
IoT and LoRaWAN-assisted real-time indoor air quality monitoring and automation system for enhancing passenger safety [15]	CO, PM, Oxygen (O_2), temperature, humidity	ESP32 LoRaWAN	AWS IoT Core	In-vehicle AQM and passenger safety; Automated responses (window opening, alarms, mobile notifications) for hyperthermia/toxic gas; Fast response times (1.2–2.3 s).	Computational overhead for real-time inference; Signal attenuation in challenging environments (underground garages); Actuator response time variability; False alarms management
Low cost sensor with LoRaWAN Connectivity and Machine Learning-based	CO, PM temperature, humidity	Murata CMWXIZZABZ-078 chipset	Gateway not used (data routed	Linear regression for temperature and humidity: mean absolute percentage error (MAPE)= 48.71% and $R^2 = 0.607$;	LoRaWAN gateway not used effectively; the authors used WiFi to route data instead

calibration for AQMS [16]			through WiFi)	ANN: MAPE= 38.89% and R^2 = 0.78	
Our proposed multi-node LoRaWAN based AQMS	CO_2, CO, NH_3, $PM_{2.5}$, PM_{10},temperature and humidity	Nucleo-WL55JC1 and Arduino MKR WAN 1310	RAK WisGate Edge Lite 2	Multi-node and diverse controllers used to analyse AQMS reliability; multi-gas detection; interactive dashboard	Application of machine learning for effective prediction

2. LoRaWAN Based AQMS System Design

In this section, we have discussed the system design of the proposed LoRaWAN based AQMS. The developed AQMS adopts a LoRaWAN-based architecture to enable efficient data transmission from distributed sensor nodes to a centralized cloud platform. As illustrated in Figure 1, the design incorporates four fundamental components that collectively ensure sensing, data collection, transmission, storage and visualization. The architecture demonstrates the complete communication pathway from edge devices to cloud infrastructure using LoRaWAN communication. Moreover, Figure 2 presents system workflow for integrating sensor nodes with a LoRaWAN gateway, cloud services, and data visualization platforms for real-time monitoring. These system components are discussed below.

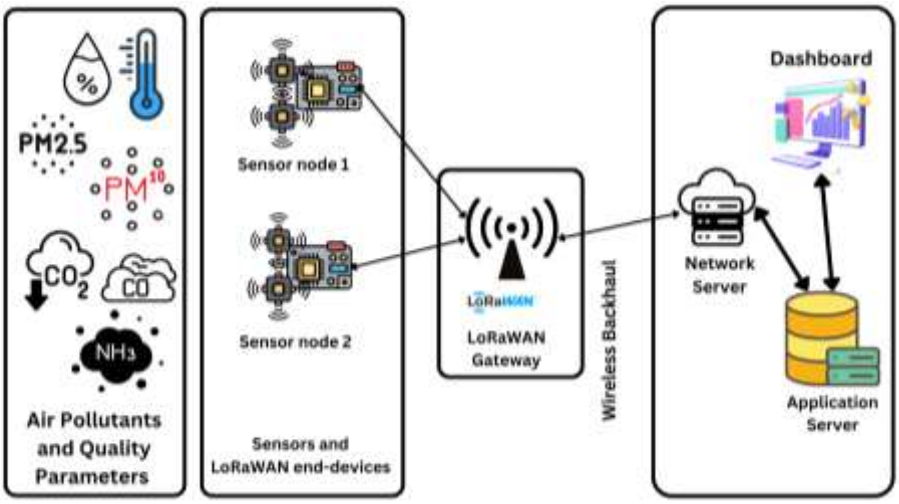


Figure 1. System design showing LoRaWAN-based AQMS.

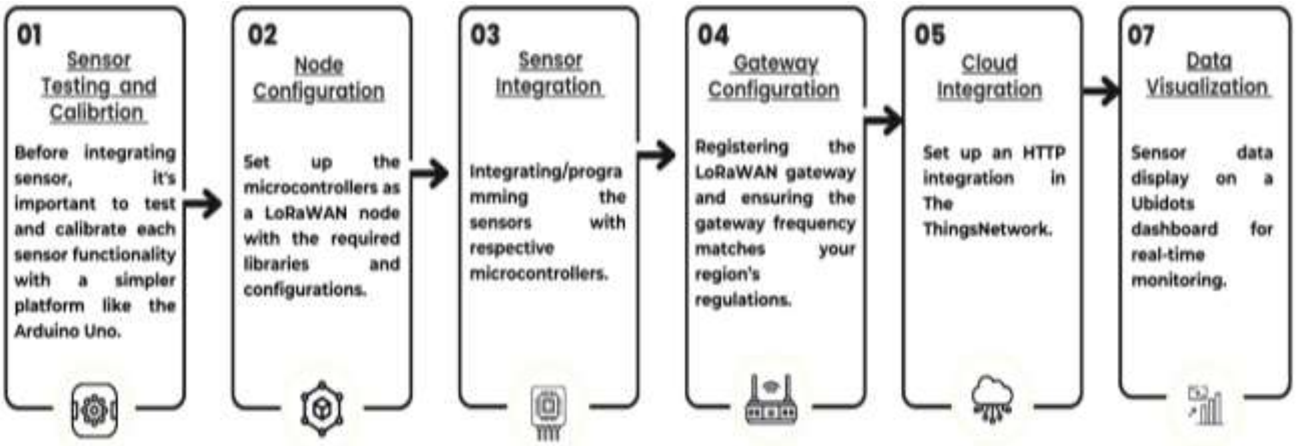


Figure 2. System workflow for integrating sensor nodes with a LoRaWAN gateway, cloud services, and data visualization platforms for real-time monitoring.

2.1. Sensor Nodes

The foundation of our system lies in the sensor nodes, which are responsible for collecting environmental data. Two sensor nodes, each equipped with LoRaWAN capable microcontrollers and sensors tailored to monitor various environmental parameters. These nodes measure temperature, humidity, gas concentrations of CO, CO_2, NH_3, and levels of particulate matter (PM2.5 and PM10). Data transmission occurs at regular intervals, a strategy that ensures efficient power consumption while maintaining the necessary frequency of data capture.

2.2. LoRaWAN Gateway

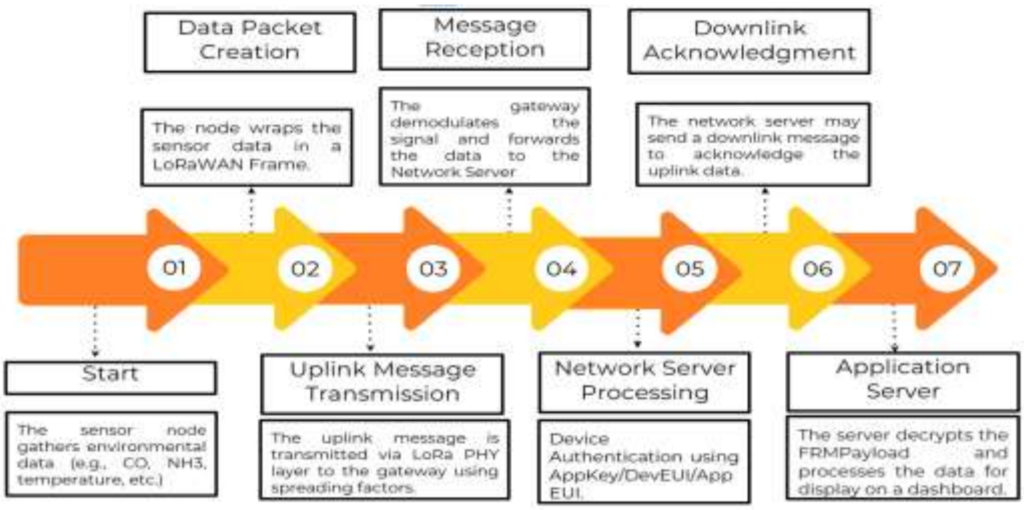
Serving as intermediary between the sensor nodes and the network server, LoRaWAN gateway is crucial for the system's communication infrastructure. In our developed system, a LoRaWAN gateway operates within the designated frequency band, adhering to local regulatory standards, enabling establishment of a connection to the local network, and integrating the gateway with the network server. This setup ensures that data collected from various environmental sensors are efficiently transmitted to the central system without significant loss or delay.

2.3. Network Server

At the core of the data management process is the network server, which handles critical tasks such as device authentication, data routing, and adaptive data rate control. Each sensor node is registered on the network server and assigned unique identifiers to maintain secure and organized communication channels. Upon receiving data packets from the gateway, the network server processes these packets by decoding the payload and routing the information to the appropriate application server. This component ensures that data integrity is maintained, and that the system can scale efficiently as more sensor nodes are added to the network.

2.4. Application Server

The application server is the endpoint where data storage, visualization, and analysis occur. Sensor data transmitted from the nodes are integrated into the application server, with each node registered as a distinct device. Specific data variables corresponding to each sensor are linked to these devices, facilitating organized data management. Additionally, the application server archives historical data, enabling users to conduct trend analyses and identify patterns over time. This approach to data visualization and storage ensures that stakeholders have continuous access to insights derived from the environmental monitoring system. Figure 3 depicts the process where data packets containing sensor data is created, transmitted and received at the application server, along with downlink acknowledgement.



01 **Start**: The sensor node gathers environmental data (e.g., CO, NH3, temperature, etc.)

02 **Data Packet Creation**: The node wraps the sensor data in a LoRaWAN Frame.

03 **Uplink Message Transmission**: The uplink message is transmitted via LoRa PHY layer to the gateway using spreading factors.

04 **Message Reception**: The gateway demodulates the signal and forwards the data to the Network Server

05 **Network Server Processing**: Device Authentication using AppKey/DevEUI/App EUI.

06 **Downlink Acknowledgment**: The network server may send a downlink message to acknowledge the uplink data.

07 **Application Server**: The server decrypts the FRMPayload and processes the data for display on a dashboard.

Figure 3. Workflow process of data packet creation, message transmission and reception and acknowledgement mechanism.

3. Development of LoRaWAN based AQMS

The proposed system comprises essential hardware and software components selected for efficient data transmission and LoRaWAN compatibility which are discussed in subsequent subsections. Sensor nodes transmit encrypted data packets to a RAK WisGate Edge Lite 2 gateway [17], which forwards measurements to TTN [18] for cloud processing before final storage and visualization in Ubidots [19]. The hardware components of this project comprise two distinct sensor nodes, each equipped with different microcontrollers and sensors to monitor specific climate parameters, and a LoRaWAN gateway that facilitates communication between the nodes and the cloud platform.

3.1. Sensor Calibration and Node Configuration

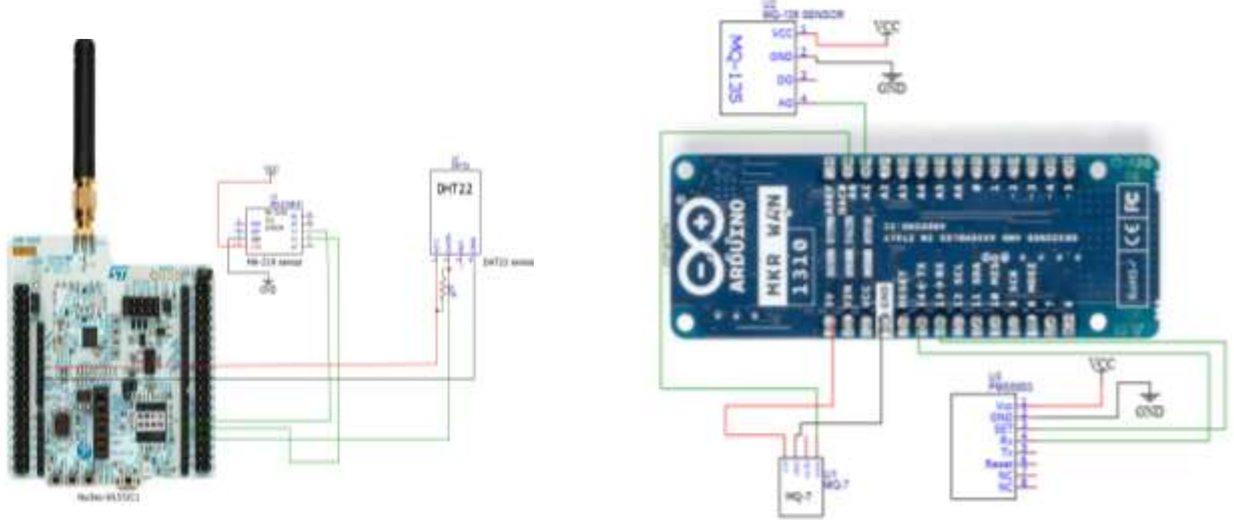
Prior to deployment, all sensors underwent rigorous calibration to ensure measurement accuracy. The DHT22 temperature/humidity sensor was validated against laboratory-grade references, showing less than ±0.5 °C and less than ±2% RH deviation in controlled environments. For gas sensors, the MHZ19B CO_2 detector was baseline-tested against atmospheric reference values (400 ppm), while MQ-series sensors were configured using manufacturer-provided sensitivity curves with software compensation for environmental variables. The PMS5003 particulate matter sensor demonstrated less than 5% variation during extended stability testing, confirming its readiness for field deployment.

For this system, two distinct sensor node configurations were developed using different microcontroller platforms. Table 2 summarizes the details of the sensors, controllers Sensor Node 1 comprises of STM32 Nucleo-64 development board STM32WL55JC1 [20] as shown in Figure 4a, which integrates a STM32WL LoRa SoC, operating at 867MHz with SF10 modulation. This configuration achieves 10 km line-of-sight range while complying with 1% duty cycle regulations. Node 2 comprises of the Arduino MKR WAN 1310 [21] controller as shown in Figure 4b combined with MQ-135, MQ-7, and PMS5003 with a SAMD21 microcontroller.

Table 2. Summary of sensors and controllers for each node.

Sensor Node	Controller	Sensors	Measured Parameters
Sensor node 1	STM32 Nucleo-64 development board (STM32WL55JC1)	DHT22	temperature and humidity
		MHZ19B	CO_2

Sensor node 2	Arduino MKR WAN 1310 (Atmel SAMD21)	MQ-7 MQ137 PMS5003	CO NH_3 airborne particulate concentrations



(**a**) (**b**)

Figure 4. Schematics of (**a**) Nucleo-WL55JC1 node connected with MH-Z19 and DHT22 sensors and (**b**) Arduino MKR WAN 1310 node connected with MQ-135, MQ-7, and PMS5003 sensors.

3.2. LoRaWAN Gateway Configuration and Communication with Sensor nodes

The RAK WisGate Edge Lite 2 gateway is used to connect the sensor nodes to the LoRaWAN network. It operates in the frequency band of 867 MHz, ensuring compliance with local regulations. The gateway supports up to 8 channels and can handle data from thousands of nodes simultaneously. The gateway was configured to ensure reliable communication between the sensor nodes and the network server. Table 3 summarizes the key settings and parameters applied to the gateway. The LoRaWAN gateway was configured to ensure reliable communication between the sensor nodes and the network server. Figure 6a depicts the physical implementation of Sensor node 1 and Figure 6b shows the implementation of Sensor node 2. Moreover, the figure also depicts the RAK WisGate Edge lite 2 gateway used to connect sensor nodes 1 and 2 with the network server. Details of server development and connection as well as cloud integration is provided in next section.

Table 3. Summary of gateway parameters.

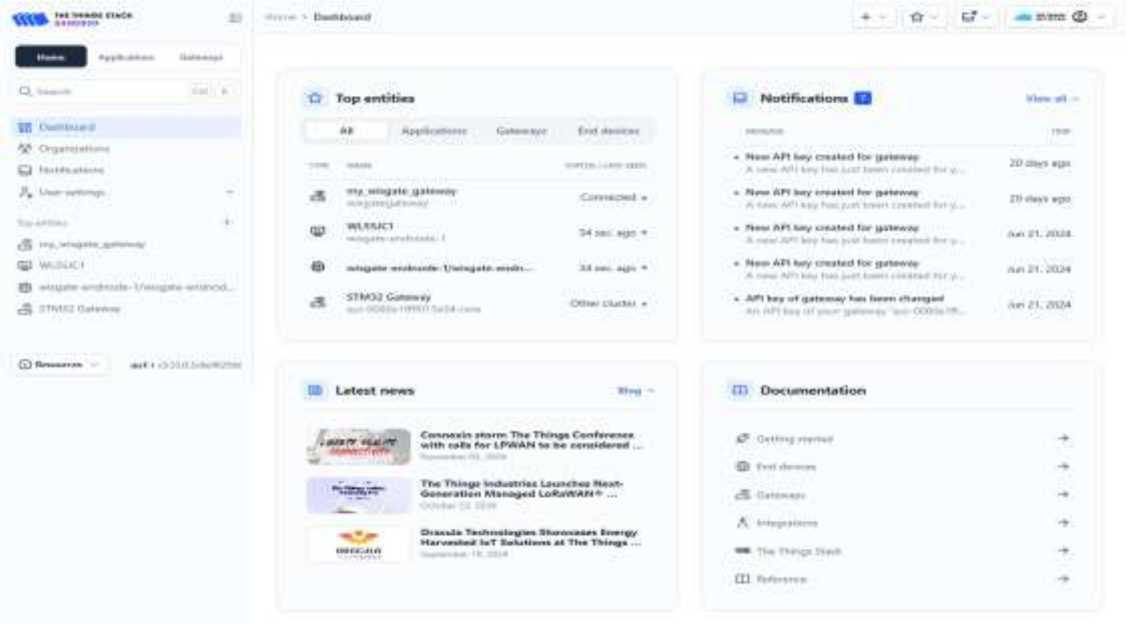
Parameter	Configuration
Frequency Range	863–870 MHz
Transmit Power	Up to 20 dBm (100 mW)
Spreading Factor (SF)	SF10
Sensitivity	−125 dBm (125 kHz bandwidth)
Bandwidth	125 kHz
Coding Rate	4/5
Payload Size	Up to 51 bytes (for SF10)
Data Rate	~5.5 kbps (125 kHz bandwidth)
Connectivity	Ethernet and Wi-Fi
Antenna	Integrated dual-band antenna

(**a**) (**b**)

Figure 5. Physical implementation of (**a**) Sensor Node 1 (**b**) Sensor Node 2, along with RAK WisGate Edge Lite 2 gateway responsible for relaying data from sensor nodes to the network server.

3.3. Server Configuration and Cloud Integration

The system's cloud integration was implemented through TTN platform, which serves as the central network server for LoRaWAN data aggregation. During the gateway configuration process, two critical API keys were generated to ensure secure and functional operation. The primary LoRaWAN Network Server (LNS) key was created with specific permissions for traffic exchange, enabling both uplink and downlink communication between the gateway and TTN servers. A secondary Configuration and Update Server (CUPS) key was implemented to handle remote management functions, including firmware updates and configuration changes. Secure authentication was established using Transport Layer Security (TLS) protocol, specifically configured for the Asia-Pacific server cluster (au1.cloud.thethings.network) to optimize regional performance. The complete integration was validated through the TTN console interface, which provided real-time confirmation of successful packet transmission from edge devices to the cloud infrastructure. Figure 6 shows the successful registration of the LoRaWAN gateway with The Things Stack. The figure also depicts connectivity of the sensor nodes as well through the gateway. Once the gateway is successfully integrated with the cloud, the next step would be to develop data processing and visualization system to effectively display sensor data as well as performance indicators of the LoRaWAN network.



- New API key created for gateway — 20 days ago
- New API key created for gateway — 20 days ago
- New API key created for gateway — Jun 21, 2024
- New API key created for gateway — Jun 21, 2024
- API key of gateway has been changed — Jun 21, 2024

Connexin storm The Things Conference with calls for LPWAN to be considered ...

The Things Industries Launches Next-Generation Managed LoRaWAN® ...

Dracula Technologies Showcases Energy Harvested IoT Solutions at The Things ...

Figure 6. Screenshots illustrating Successful registration of LoRaWAN gateway on The Things Stack.

3.4. Data Processing and Visualization System

The implemented data processing pipeline begins when the end nodes transmit encoded sensor measurements via LoRaWAN to TTN cloud platform. Here, a custom decoder processes the raw data packets, extracting air quality parameter readings while preserving critical metadata including signal strength indicators and precise timestamps. The cloud integration employs a secure HTTP web hook that automatically routes decoded measurements to the Ubidots IoT platform. The integration of sensor data from the sensor nodes into Ubidots was carried out following the official The Things Stack to Ubidots integration guide to ensure a smooth and automated data flow.

The process began with registering the nodes as a device in TTS, where it transmitted sensor data. To establish this connection, a new Webhook was created in TTS using the Ubidots Cloud Integration template. This template streamlined the configuration by automatically mapping device uplinks to corresponding variables in Ubidots. The Webhook was set up with the necessary Ubidots token and device labels, ensuring that each incoming data packet was parsed and stored correctly. Once received in Ubidots, the sensor nodes were registered as a device, and its sensor readings were assigned to specific data variables. The incoming sensor data from nodes follow a structured decoding and processing workflow, as illustrated in Figure 7. Ubidots first checks for an uplink message. If an uplink is present, the system extracts gateway details such as Received Signal Strength Indicator (RSSI), Signal to Noise Ratio (SNR), timestamp, frame counter, and port. The payload is then decoded, logged, and formatted into an Ubidots-compatible payload. Finally, the processed data is sent to Ubidots for storage and visualization, ensuring accurate data reception, decoding, and integration for reliable environmental monitoring. The values were successfully received in Ubidots and stored as time-series data linked to the respective sensor variables.

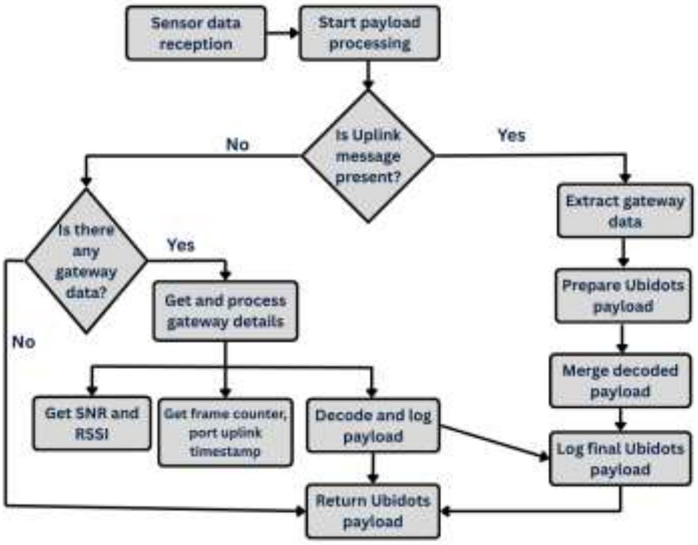


Figure 7. Flowchart depicting the structured decoding and processing workflow for incoming sensor data.

4. Results and Discussion

The deployment and testing of the LoRaWAN-based sensor nodes provided valuable insights into their performance, data accuracy, and network reliability. The results obtained from both Sensor node 1 and Sensor node 2 demonstrated the system's capability to efficiently monitor multiple environmental parameters in a confined laboratory setting.

Sensor node 1 has been implemented for monitoring temperature, humidity and CO_2 concentration using a combination of DHT22 and MH-Z19 sensors respectively. The data was transmitted via the LoRaWAN gateway to Ubidots, where it was logged and visualized in real time. Moreover, Sensor node 2 was implemented for monitoring CO and PM using ZE07-CO and PMS5003 sensors respectively. The PMS5003 sensor successfully measured PM2.5 and PM10 concentrations, providing valuable air quality insights. The data showed expected variations in particulate levels based on activities within the laboratory, such as human movement and ventilation changes. Figure 8 depicts a sample of sensors data received and displayed on the Ubidots.

The Ubidots dashboard as shown in Figure 9 provides real-time monitoring of various parameters related to environmental conditions and network performance. The device labeled wisgate-endnode-1 displays seven key variables, each represented by a data card. These parameters include CO_2 Level, reflecting the concentration of carbon dioxide in the environment. The humidity level is measured at 52.3%, providing insights into atmospheric moisture. The room temperature is recorded at 22 °C, indicating ambient thermal conditions. In addition to environmental data, the dashboard also displays communication-related metrics. The RSSI of the gateway, shown as -30 dBm, represents the signal strength received from the node. The SNR is recorded at 13.25 dB. The Frame Counter, displayed as 12, tracks the number of packets sent by the nodes, ensuring data integrity and transmission consistency. This structured visualization enables efficient monitoring of both environmental and network parameters. While the data is currently presented as numerical values, future enhancements may include graphical representations such as time-series plots and gauges to improve trend analysis and real-time decision-making.

The decoded payload data provides real-time sensor readings, including temperature, humidity, and CO_2 levels as shown in Figure 15. The data packets, received through multiple frequencies and data rates, were extracted, processed, and formatted before being stored in Ubidots for visualization. The decoded values ensure accurate environmental monitoring and facilitate further analysis of trends over time.

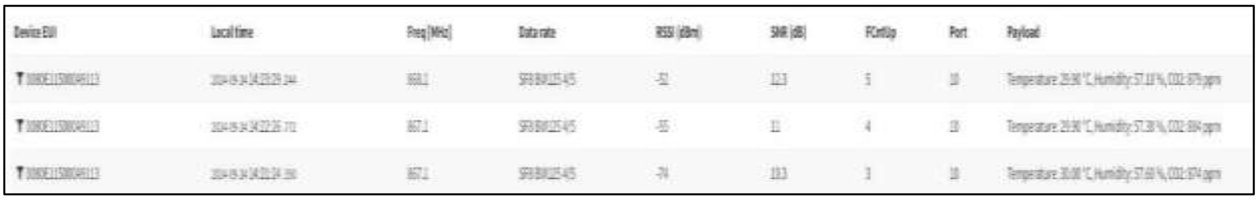


Figure 8. Sample of sensor data successfully received and displayed in Ubidots with real-time updates.

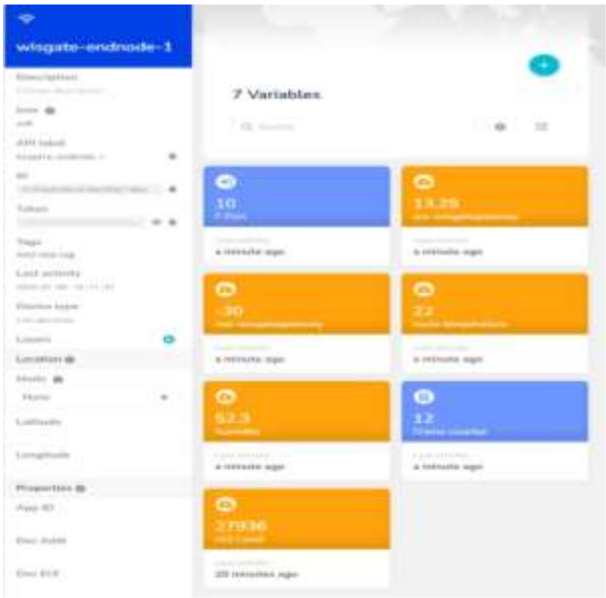


Figure 9. The dashboard displays real-time sensor data and network metrics for monitoring and analysis.

Overall, the sensor nodes achieved a 98% packet delivery rate, confirming reliable data transmission over the LoRaWAN network. Packet loss was minimal, with occasional delays observed during network congestion. Both nodes operated efficiently on battery power, with the Sensor node 1 consuming an average of 20 mA in active mode, while the Sensor node 2 operated at 15 mA. These values ensured extended operation for remote deployment. The data transmission from sensor nodes to Ubidots experienced an average delay of 2.5 seconds, making it suitable for real-time environmental monitoring applications.

5. Conclusions

In this paper, we have presented successfully developed LoRaWAN-based AQMS. The implemented solution effectively tracks multiple air quality parameters including temperature, humidity, CO_2, NH_3, CO, and PM concentrations. Through careful system design and integration, the network achieved excellent reliability with a 98% packet delivery rate while maintaining low power consumption suitable for extended deployments. Two complementary sensor node architectures were implemented and evaluated using STM32 and Arduino controllers. The sensor nodes were successfully integrated with cloud through LoRaWAN gateway and Ubidots dashboard platform. The results highlight several key advantages of the LoRaWAN approach for AQMSs. These characteristics make the solution particularly suitable for smart city applications and industrial environments where reliable, distributed monitoring is required.

Author Contributions: Conceptualization, S.A., I.A., and M.I.A.; methodology, I.A.; software, T. and A.A.; validation, T., and S.A.; formal analysis, I.A. and A.A.; investigation, S.A.; resources, M.I.A.; writing—original draft preparation, T. and S.A.; writing—review and editing, I.A, M.I.A., and A.A.; visualization, T., S.A., and A.A.; supervision, I.A. and M.I.A.; project administration, S.A.; funding acquisition, S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Sindh Higher Education Commission Sindh Research Support Program project 24/18 titled "Mob-Air: Indigenous development of mobile air quality monitoring system for public health and safety".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. O'Connor, S.; O'Connor, P.F.; Feng, H.A.; Ashley, K. Gravimetric Analysis of Particulate Matter using Air Samplers Housing Internal Filtration Capsules. *Gefahrstoffe Reinhalt. Der Luft Air Qual. Control* **2014**, *74*, 403-410.
2. Selvam, A.P.; Al-Humairi, S.N.S. Environmental impact evaluation using smart real-time weather monitoring systems: a systematic review. *Innov. Infrastruct. Solut.* **2024**, *10*, 13. https://doi.org/10.1007/s41062-024-01817-7.
3. Helmig, D. Air analysis by gas chromatography. *J. Chromatogr. A* **1999**, *843*, 129-146. https://doi.org/10.1016/S0021-9673(99)00173-9.
4. Gao, Y.; Dong, W.; Guo, K.; Liu, X.; Chen, Y.; Liu, X.; Bu, J.; Chen, C. Mosaic: A low-cost mobile sensing system for urban air quality monitoring. In Proceedings of the IEEE INFOCOM 2016—The 35th Annual IEEE International Conference on Computer Communications, San Francisco, CA, USA, 10–14 April 2016; pp. 1–9.
5. Castell, N.; Dauge, F.R.; Schneider, P.; Vogt, M.; Lerner, U.; Fishbain, B.; Broday, D.; Bartonova, A. Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? *Environ. Int.* **2017**, *99*, 293-302. https://doi.org/10.1016/j.envint.2016.12.007.
6. Kadri, A.; Yaacoub, E.; Mushtaha, M.; Abu-Dayya, A. Wireless sensor network for real-time air pollution monitoring. In Proceedings of the 2013 1st International Conference on Communications, Signal Processing, and their Applications (ICCSPA), Sharjah, United Arab Emirates, 12–14 February 2013; pp. 1–5.
7. Dhingra, S.; Madda, R.B.; Gandomi, A.H.; Patan, R.; Daneshmand, M. Internet of Things Mobile–Air Pollution Monitoring System (IoT-Mobair). *IEEE Internet Things J.* **2019**, *6*, 5577-5584. https://doi.org/10.1109/JIOT.2019.2903821.
8. Messan, S.; Shahud, A.; Anis, A.; Kalam, R.; Ali, S.; Aslam, M.I. Air-MIT: Air Quality Monitoring Using Internet of Things. *Eng. Proc.* **2022**, *20*, 45.
9. Petäjäjärvi, J.; Mikhaylov, K.; Pettissalo, M.; Janhunen, J.; Iinatti, J. Performance of a low-power wide-area network based on LoRa technology: Doppler robustness, scalability, and coverage. *Int. J. Distrib. Sens. Netw.* **2017**, *13*, 1550147717699412. https://doi.org/10.1177/1550147717699412.
10. Semtech Corporation: LoRa Technology Overview. **2023**.
11. Jabbar, W.A.; Subramaniam, T.; Ong, A.E.; Shu'Ib, M.I.; Wu, W.; de Oliveira, M.A. LoRaWAN-Based IoT System Implementation for Long-Range Outdoor Air Quality Monitoring. *Internet Things* **2022**, *19*, 100540. https://doi.org/10.1016/j.iot.2022.100540.
12. Camarillo-Escobedo, R.; Flores, J.L.; Marin-Montoya, P.; García-Torales, G.; Camarillo-Escobedo, J.M. Smart Multi-Sensor System for Remote Air Quality Monitoring Using Unmanned Aerial Vehicle and LoRaWAN. *Sensors* **2022**, *22*, 1706.
13. Truong, T.V.; Nayyar, A.; Masud, M. A novel air quality monitoring and improvement system based on wireless sensor and actuator networks using LoRa communication. *PeerJ Comput. Sci.* **2021**, *7*, e711. https://doi.org/10.7717/peerj-cs.711.
14. TagIO.

15. Abubeker, K.M.; Prajitha, C.; Rinesh, S.; Arun, M.; Senthil Kumar, A.P. Internet of Things and LoRaWAN-assisted real-time indoor air quality monitoring and automation system for enhancing passenger safety. *Int. J. Low-Carbon Technol.* **2025**, *20*, 1427-1439. https://doi.org/10.1093/ijlct/ctaf083.
16. Ali, S.; Glass, T.; Parr, B.; Potgieter, J.; Alam, F. Low Cost Sensor With IoT LoRaWAN Connectivity and Machine Learning-Based Calibration for Air Pollution Monitoring. *IEEE Trans. Instrum. Meas.* **2021**, *70*, 1–11. https://doi.org/10.1109/TIM.2020.3034109.
17. RAK Wireless, RAK WisGate Edge Lite 2 documentation.
18. The Things Network.
19. Ubidots: IoT Data Visualization Platform. **2023**.
20. STM32 Nucleo-64 development board with STM32WL55JC 1.
21. Arduino MKR WAN 1310.