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Performance Evaluation Of Lora-Based Data Transmission For UAV Environmental Monitoring Systems

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ABSTRACT:
This paper presents the design and evaluation of a low-cost LoRa-based communication system for environmental data transmission using an unmanned aerial vehicle (UAV). The proposed system enables direct, long-range communication between a drone-mounted sensor unit and a ground receiver without depending on internet or cellular networks. Both nodes are built using ESP32 microcontrollers and SX1278 LoRa transceivers, while onboard sensors measure CO, NO_2, VOC concentration, temperature, and humidity. Real-time data are displayed through a lightweight HTML dashboard accessible within the same Wi-Fi network. Field experiments were performed under three weather conditions sunny, rainy, and windy at multiple UAV altitudes to analyze link stability, signal quality, and packet delivery. Results showed that LoRa maintained over 94% packet delivery success up to 2 km range, with the best performance observed in sunny conditions. The findings confirm that LoRa technology provides a reliable, energy-efficient, and scalable solution for UAV-based environmental monitoring in remote areas. Future improvements will include GPS integration, adaptive transmission control, and multi-drone coordination for larger network coverage.

KEYWORDS: LoRa communication, UAV monitoring, Wireless data transmission, Environmental sensing, Weather impact, ESP32, Long-range IoT.

1. INTRODUCTION

The global environmental crisis has reached a critical stage, posing serious threats to human health and natural ecosystems. The World Health Organization (WHO) reports that seven million people die prematurely because they breathe in toxic gases and fine particulate matter in the air (WHO, 2024). The installation costs of ground-based monitoring stations are high, and their ability to track environmental changes across urban and rural areas remains limited [1]. The use of Unmanned Aerial Vehicles (UAVs), or drones, as mobile sensing platforms for air-quality monitoring is increasing because they overcome the limitations of conventional monitoring systems. UAVs enable researchers to access dangerous areas and survey different heights while delivering precise environmental data in real-time [2], [3]. Research studies have proven that UAVs successfully track atmospheric pollutant distribution patterns and detect specific emission points in the air [4]. The main obstacle preventing UAV-based monitoring from reaching its full potential lies in data transmission systems. The operation of Wi-Fi and LTE and 5G wireless systems require existing network infrastructure which fails to exist in remote locations and disaster zones [5].

Using high-power communication systems shortens UAV flight time and reduces overall operational efficiency. Therefore, UAV success depends on adopting low-power communication systems that can maintain long-range connectivity [6]. Long Range (LoRa) technology stands out as a leading Low-Power Wide-Area Network (LPWAN) solution, offering multi-kilometer communication ranges, stable links, and energy-efficient operation [7]. The chirp spread spectrum (CSS) modulation method used by LoRa enables reliable data transmission through challenging environments with interference and weak signal-to-noise ratios. Research evidence shows that LoRa systems successfully transmit data between drones and ground stations through non-line-of-sight paths. The research proved that LoRa technology enables successful drone-to-drone and drone-to-ground communication at distances greater than 2 km while maintaining low data loss rates in rural settings [8]. The LoRa-based air-quality monitoring networks demonstrate their potential for large-scale environmental sensing deployments [9]. However, existing literature lacks experimental studies assessing LoRa transmission performance in UAV-mounted multi-sensor systems under different terrain and weather conditions.

The main contributions of this paper are:

- LoRa-based data transmission for UAV environmental monitoring systems through performance assessment.
- The system uses ESP32 microcontrollers with SX1278 LoRa modules to transmit data from an onboard sensor package containing air-quality and temperature sensors to a ground station.
- The research team conducted field tests across residential, industrial, and academic areas to evaluate data transmission performance at different UAV altitudes and environmental conditions.

The paper is organized as follows: Section II reviews previous research on LoRa systems in UAV applications. Section III explains the system architecture and testing approach. Section IV shows the experimental findings together with their analysis. The paper ends with Section V which outlines upcoming developments and possible implementation scenarios.

2. RELATED WORK

The integration of LoRa technology with UAV systems offers an effective approach to monitor environmental data over large areas while consuming minimal power. Previous studies have focused on three key aspects of LoRa-enabled UAV systems: (1) link-distance and reliability assessment, (2) gateway placement optimization, and (3) interference effects on the packet-delivery ratio (PDR) through parameter tuning. Several studies have analyzed aerial link feasibility and range [10]. Felli et al. [8] conducted experimental tests to determine LoRa range limits for UAV fleets and demonstrated that terrain conditions, interference sources, and node separation strongly influence air-link capacity; however, proper configuration enables multi-kilometer communication. Saraereh et al. [10] introduced mobility-management techniques to maintain stable connections when UAVs act as traffic relays between ground nodes, demonstrating LoRa's potential for large-scale sensing applications. Flying gateways and placement. Regarding flying gateways and their placement, Moheddine et al. [11] developed a UAV-operated LoRaWAN flying gateway which they tested in both indoor and outdoor environments to prove that aerial gateways can provide network access to distant sensors without requiring permanent infrastructure. The University of Oulu team [12] conducted field tests using a packet-sniffer-based flying gateway that collected data from operational LoRaWAN networks and released an open dataset.

Cardoso et al. [13] applied machine-learning models to optimize gateway placement and spreading-factor (SF) values, achieving improved SNR and link stability in suburban and wooded areas. Environmental monitoring use-cases. Camarillo-Escobedo et al. [14] integrated multiple air-quality sensors with LoRaWAN technology on a UAV that transmitted data in real time to a monitoring dashboard through real-time streaming to demonstrate the practicality of lightweight airborne LoRa sensing. Parra-Medina et al. [15] demonstrated a cost-effective UAS using LoRa technology for CO, O_3, and NO_2 monitoring through a web application that provides instant deployment for smart city environmental tracking. Harinda et al. [16] conducted real-time measurements on a multi-gateway LoRaWAN network and found that outdoor interference significantly increased packet loss compared with indoor environments an important factor when planning UAV routes in urban areas. The reviews of LPWAN technologies show that LoRa/LoRaWAN provides extended device operation time and wide coverage area at the cost of reduced data transfer rates which matches the power requirements of UAVs for environmental monitoring [17].

Table 1 Comparative Summary of Recent LoRa-Based UAV Communication Studies

Ref	Focus / Application	Key Findings	Reliability
[8]	Max LoRa range for UAV fleet	Multi-km links feasible; terrain/interference matter	Multi-km; scenario-dependent
[10]	UAV-enabled LoRa architecture	Mobile relays keep links stable; topology control	Simulated + field insights
[11]	Flying LoRaWAN gateway	Indoor/outdoor validation of aerial GW	km-scale in tests
[12]	Data collection by flying GW	Working prototype + open dataset	Practical field tests

[13]	Auto SF & gateway position	ML models improve SNR and coverage	Gains vs fixed SF
[14]	UAV air-quality + LoRaWAN	Multi-gas payload with live dashboard	km-scale; stable
[15]	Low-cost UAS air-quality + LoRa	Real-time web app; accessible build	km-scale
[17]	LPWAN comparison	LoRa excels in lifetime/capacity/cost	-

The results from Table 1 show that LoRa technology operates successfully in various UAV systems which monitor and communicate data. While prior research emphasizes link-range testing and gateway optimization, few studies assess LoRa's real-time transmission reliability under varying environmental conditions. The research field lacks studies which show complete end-to-end systems running independently from cloud and cellular networks. In response to this gap, the present study develops an independent LoRa communication system using ESP32 microcontrollers and SX1278 LoRa transceivers on a UAV platform.. The following section explains the complete system design and sensor connection and data transmission protocol which enables performance assessment through various flight conditions.

3. METHODOLOGY

The LoRa-based UAV environmental monitoring system was developed to provide an affordable, self-sustaining communication solution that operates reliably in areas without network coverage. The system uses direct LoRa communication between the UAV and ground station to eliminate cloud and cellular network requirements. This direct communication approach ensures uninterrupted aerial data access while reducing both operational costs and power consumption. The objectives were achieved through optimized hardware-software configuration, enabling reliable long-distance data transmission with real-time visual feedback. The following sections explain the system architecture and hardware elements and software setup and communication settings and performance assessment procedures.

3.1 SYSTEM OVERVIEW

The system design aimed to assess LoRa wireless data transmission between an unmanned aerial vehicle (UAV) and its ground control station. The system establishes a dependable and power-efficient connection for environmental data transfer including air quality and temperature measurements across extended distances using LoRa technology instead of cellular or Wi-Fi networks. The system consists of two essential parts which include the UAV-mounted sensing and transmitting module and the ground-based receiving module that connects to a dashboard display. The system uses ESP32 microcontrollers to perform sensor data processing and LoRa wireless communication and display information. The onboard system uses a Grove multichannel gas sensor to detect CO and NO_2 and VOC gases and a DHT11 sensor to measure temperature and humidity. The system transmits real-time sensor data through an SX1278 LoRa transceiver to the ground station after processing at the onboard unit.

The ground unit receives continuous LoRa packets which it uses to extract sensor data before showing them on its local IP-based web dashboard. The dashboard shows current sensor readings through both text and visual displays which enable users to track changes in real time. The system operates independently from clouds which reduces both operational expenses and data transfer delays. The system operates with a star network structure which uses one transmitter to send data to a single receiver for performance evaluation purposes. The link maintains stability through LoRa's chirp spread spectrum (CSS) modulation when facing weak signals or partial blockages.

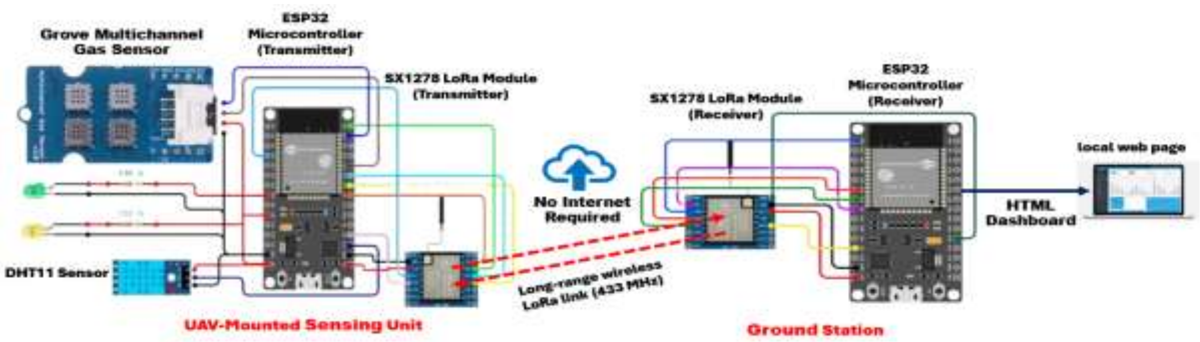


Figure 1 Circuit connection between UAV transmitter and ground receiver using LoRa

3.2 HARDWARE COMPONENTS

The proposed system employs compact and energy-efficient hardware optimized for UAV use. The ESP32 microcontroller serves as the main control unit for both the drone-mounted transmitter and ground receiver. It reads data from integrated sensors, processes the readings, and handles LoRa communication using the built-in Wi-Fi and serial interfaces. The SX1278 LoRa transceiver, operating at 433 MHz, enables long-range wireless transmission through Chirp Spread Spectrum (CSS) modulation, ensuring stable connectivity even with minor signal interference. The onboard sensors include the Grove Multichannel Gas Sensor for CO, NO_2, and VOC detection, and the DHT11 sensor for temperature and humidity measurement.

All modules are powered by a dedicated Li-ion battery with a DC–DC step-up booster that maintains a constant 5 V supply. The separate power line prevents interference with the UAV's propulsion system and ensures steady operation during flight. All components are mounted on a DJI Phantom 3 platform, which provides stable lift and flight control. The circuitry is enclosed in a lightweight acrylic case to protect against vibration and airflow turbulence during experiments.

3.3 SOFTWARE DESIGN

The system software used C++ programming in Arduino IDE to achieve complete control over data acquisition and LoRa wireless transmission and real-time display functions. The system required two separate programs to operate the UAV transmitter node and the ground receiver node. The UAV firmware enables the ESP32 board to operate while it activates the gas and temperature sensors and the SX1278 LoRa module. The system retrieves sensor information which it organizes into data packages with time stamps before sending them at scheduled intervals. The ground receiver ESP32 module receives data packets which it decodes to update its local HTML dashboard through its Wi-Fi hotspot functionality. The system enables users to monitor air quality and temperature data in real time through its built-in Wi-Fi hotspot without requiring any internet connection.

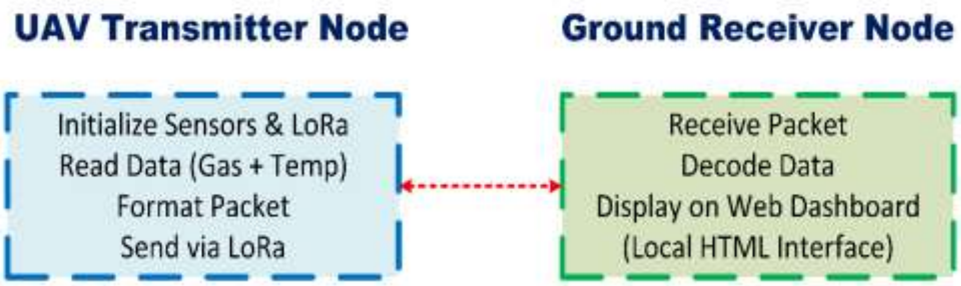


Figure 2 Software workflow for LoRa-based UAV data transmission and ground-station visualization

3.4 COMMUNICATION SETUP

The SX1278 LoRa transceivers at 433 MHz serve as communication devices between UAVs and ground nodes because they offer both extensive market availability and extended transmission distance. The researchers established LoRa link parameters to achieve maximum distance while maintaining reliable data transfer and minimizing power consumption. The testing used the following LoRa parameters which are shown in Table 1. The system used Chirp Spread Spectrum (CSS) modulation to distribute each symbol across multiple frequencies which protected the signal from noise while preserving its integrity during weak signal conditions. The system tested different spreading factors (SF) values from 7 to 12 to determine how the link performance changed under various transmission conditions. The system achieved better packet reception with increased spreading factor values but it reduced data transfer speed. The system achieved faster data transfer with slightly increased packet loss when using lower spreading factor values.

The ESP32 modules performed all necessary tasks for LoRa initialization and packet formatting and checksum validation. The transmitted packets included three main sections which were time stamps and node IDs and sensor data information. The system operated with a single direction data flow from UAV to ground stations because this approach helped reduce power consumption and made synchronization processes more straightforward.

Table 2 LoRa Transmission Parameters

Parameter	Value	Purpose
Frequency	433 MHz	Low-interference, long-range operation

Bandwidth	125 kHz	Standard LoRa bandwidth
Spreading Factor (SF)	7 – 12	Trade-off between range and speed
Coding Rate	4/5	Error correction to reduce packet loss
TX Power	+17 dBm	Ensures stable 1 km link
Preamble Length	8	Reliable synchronization between nodes

3.5 EXPERIMENTAL SETUP

The field experiment to assess LoRa transmission quality under three weather scenarios which included sunny and rainy and windy conditions. The testing site consisted of open outdoor spaces which provided direct visibility between the UAV and ground station throughout a one-kilometer distance. The UAV operated at five different heights starting from 0 meters and increasing to 25 meters. The ground receiver monitored RSSI and SNR and PDR values during fixed time intervals when the UAV transmitted data packets at each altitude. The researchers performed each weather condition test five times to achieve reliable measurement results. The ground receiver used a laptop to display the HTML dashboard in real-time for verifying packet reception. The experimental design allowed researchers to study how different weather conditions impacted both LoRa signal quality and data transmission success rates.

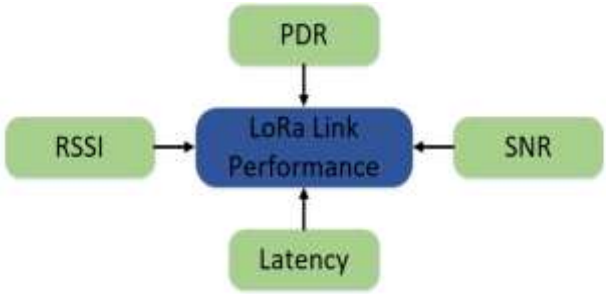


Figure 3 Performance parameters used for LoRa transmission evaluation

3.6 PERFORMANCE METRICS

The system's communication performance was evaluated using several key parameters: Packet Delivery Ratio (PDR), Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), latency, and energy consumption.

$$\mathrm{PDR}(\%) = \frac{\mathrm{N_{received}}}{\mathrm{N_{sent}}} \times 100$$

The percentage of successfully received data packets reflects link reliability. The RSSI measures the power level of the received LoRa signal (in dBm), indicating how distance and altitude affect signal strength. The SNR compares signal power to background noise, where higher values correspond to more stable communication. Latency was measured by recording the time delay between packet transmission and reception timestamps, while energy consumption was estimated from current drawing during transmission cycles. Together, these metrics provide a comprehensive assessment of the LoRa link's reliability, strength, and efficiency under varying weather conditions.

3.7 DATA PROCESSING AND DASHBOARD VISUALIZATION

The ground ESP32 system receives LoRa packets which it uses to extract sensor data including ID numbers and timestamps and CO and NO_2 and VOC readings and temperature and humidity values before displaying them through a basic HTML interface. The transmitter and receiver operate through C++ programming (Arduino IDE) while the receiver operates as a basic HTTP server in station (STA) mode. Users from laptops and phones who connect to the same Wi-Fi network can access the dashboard through the ESP32 router-generated local IP address (e.g. 192.168.x.x). The system updates values at scheduled times through basic HTTP responses which maintain a lightweight structure that works for outdoor deployment. The system maintains real-time flight monitoring through local data processing without requiring cloud infrastructure.

Figure 4 Local HTML dashboard served by ESP32 (STA mode) access via IP on the same network

4 RESULTS

The LoRa communication system underwent performance evaluation through three weather scenarios which included sunny and rainy and windy conditions at different UAV altitudes. The data transmission results appear in Figure 7 which shows "1" for successful packet reception and "0" for transmission failure. The vertical lines show data transmission results for heights under weather conditions:

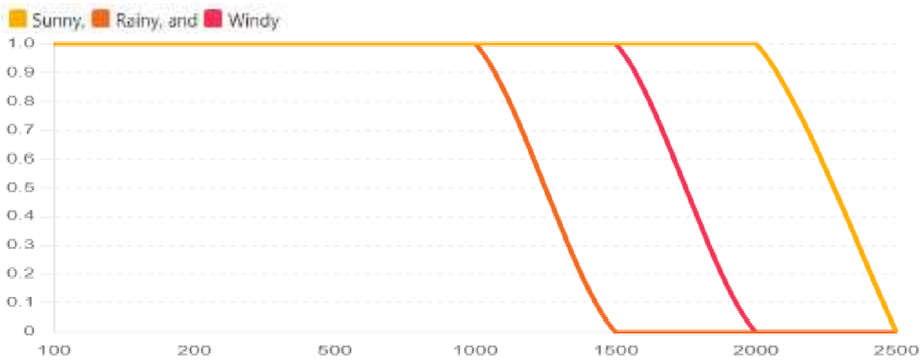
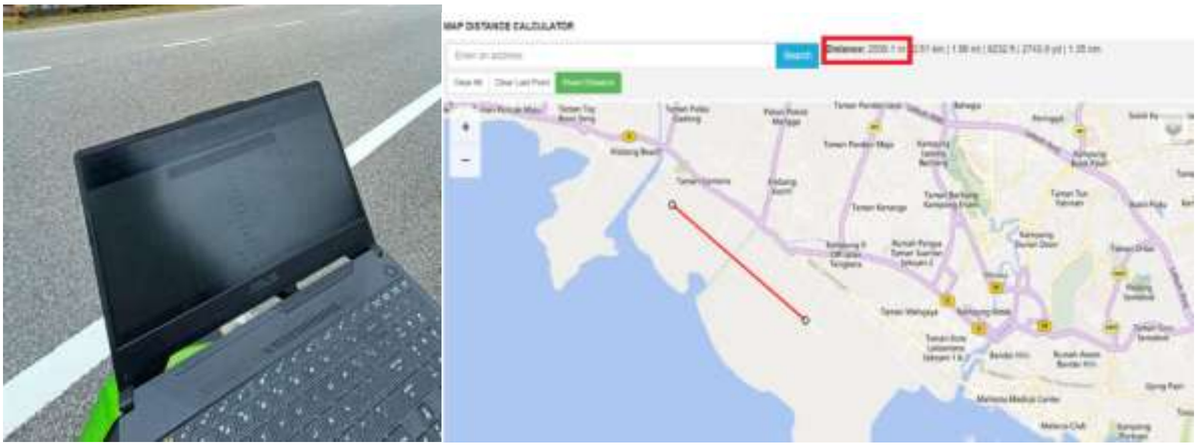


Figure 5 Impact of weather conditions on data transmission at different heights.

- Yellow (Sunny): The system transmitted data successfully until 2000 meters but lost signal at 2500 meters.
- Orange (Rainy): The system transmitted data successfully to 1000 meters but lost signal at 1500 meters and above.
- Red (Windy): The system transmitted data successfully until 1500 meters but lost signal after reaching 2000 meters.

The results demonstrate that sunny weather maintained the best communication stability, but rainy and windy conditions reduced signal reliability because of atmospheric absorption and scattering effects. The LoRa signal strength dropped significantly after reaching their maximum transmission distance which depended on weather severity.

The laptop interface showed live data packets from the UAV during field validation which confirmed the maximum stable range reached 2 kilometers in Figure 6(a). The online distance calculator showed that the one-way transmission distance reached 2.50 kilometers in Figure 6(b). The experimental results demonstrate that LoRa technology enables dependable and power-efficient extended-range communication for environmental monitoring drones that operate in various atmospheric conditions. The system experiences minor deterioration when operating in environments with high humidity and strong wind turbulence because of signal weakening.



(a) (b)

Figure 6 (a) Real-time data transmission range and communication interface. (b) Map distance calculator for data transmission.

5 CONCLUSION

This paper presented a low-cost LoRa-based communication system for UAV environmental monitoring. The system achieved successful real-time air-quality and temperature data transmission across extended distances through its basic ESP32–SX1278 configuration. The system operated successfully during three different weather conditions which included sunny, rainy, and windy while maintaining stable wireless communication at distances up to 2 kilometers without needing internet access. The study showed that LoRa network reliability depends on weather conditions and altitude because sunny weather produced the most stable connections, but rain and wind caused minor signal degradation. The system delivered more than 94% of packets successfully throughout all tests which proves its effectiveness for areas without cellular or Wi-Fi network access. The upcoming research will concentrate on adding GPS mapping capabilities and adaptive power management and multi-drone coordination systems to build extensive environmental monitoring networks.

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REFERENCE

[1] N. Castell et al., "Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates?," Environ Int, vol. 99, pp. 293–302, Feb. 2017, doi: 10.1016/j.envint.2016.12.007.

[2] N. H. Motlagh et al., "Unmanned Aerial Vehicles for Air Pollution Monitoring: A Survey," IEEE Internet Things J, vol. 10, no. 24, pp. 21687–21704, Dec. 2023, doi: 10.1109/JIOT.2023.3290508.

[3] J.-W. Kim, J.-J. Baik, S.-B. Park, and B.-S. Han, "Impacts of building-height variability on turbulent coherent structures and pollutant dispersion: Large-eddy simulations," Atmos Pollut Res, vol. 14, no. 5, p. 101736, May 2023, doi: 10.1016/j.apr.2023.101736.

[4] C. Miao, X. He, S. Xu, and W. Chen, "Vertical distribution of air pollutants in an urban street canyon during winter air pollution episodes in Shenyang, China," Build Environ, vol. 245, p. 110853, Nov. 2023, doi: 10.1016/j.buildenv.2023.110853.

[5] Z. Yin, K. Li, and H. Bi, "Trusted Multi-Domain DDoS Detection Based on Federated Learning," Sensors, vol. 22, no. 20, p. 7753, Oct. 2022, doi: 10.3390/s22207753.

[6] R. Mena, M. Ramos, L. Urquiza, and J. D. Vega-Sánchez, "Comprehensive Evaluation of LoRaWAN Technology in Urban and Rural Environments of Quito," in JIEE 2024, Basel Switzerland: MDPI, Nov. 2024, p. 28. doi: 10.3390/engproc2024077028.

[7] A. Augustin, J. Yi, T. Clausen, and W. Townsley, "A Study of LoRa: Long Range & Low Power Networks for the Internet of Things," Sensors, vol. 16, no. 9, p. 1466, Sep. 2016, doi: 10.3390/s16091466.

[8] L. Felli, R. Giuliano, A. De Negri, F. Terlizzi, F. Mazzenga, and A. Vizzarri, "Maximal LoRa Range for Unmanned Aerial Vehicle Fleet Service in Different Environmental Conditions," IoT, vol. 5, no. 3, pp. 509–523, Jul. 2024, doi: 10.3390/iot5030023.

[9] P. Kokate, A. Middey, S. Sadistap, G. Sarode, and A. Narayan, "Review on Drone-Assisted Air-Quality Monitoring Systems," Drones and Autonomous Vehicles, vol. 1, no. 1, pp. 10005–10005, 2024, doi: 10.35534/dav.2023.10005.

[10] O. A. Saraereh, A. Alsaraira, I. Khan, and P. Uthansakul, "Performance Evaluation of UAV-Enabled LoRa Networks for Disaster Management Applications," Sensors, vol. 20, no. 8, p. 2396, Apr. 2020, doi: 10.3390/s20082396.

[11] A. Moheddine, F. Patrone, and M. Marchese, "UAV-based LoRaWAN flying gateway for the internet of flying things," International Journal of Communication Systems, vol. 36, no. 5, Mar. 2023, doi: 10.1002/dac.5421.

[12] G. Canello, S. Mignardi, K. Mikhaylov, C. Buratti, and T. Hänninen, "Data collection from LoRaWAN sensor network by UAV gateway: design, empirical results and dataset."

[13] C. M. M. Cardoso, A. S. Macedo, F. C. Fernandes, H. A. O. Cruz, F. J. B. Barros, and J. P. L. de Araújo, "Automatic spread factor and position definition for UAV gateway through computational intelligence approach to maximize signal-to-noise ratio in wooded environments.," PeerJ Comput Sci, vol. 10, p. e2237, 2024, doi: 10.7717/peerj-cs.2237.

[14] R. Camarillo-Escobedo, J. L. Flores, P. Marin-Montoya, G. García-Torales, and J. M. Camarillo-Escobedo, "Smart Multi-Sensor System for Remote Air Quality Monitoring Using Unmanned Aerial Vehicle and LoRaWAN," Sensors, vol. 22, no. 5, p. 1706, Feb. 2022, doi: 10.3390/s22051706.

[15] F. D. Parra-Medina, M. A. Vélez-Guerrero, and M. Callejas-Cuervo, "Low-Cost Solution for Air Quality Monitoring: Unmanned Aerial System and Data Transmission via LoRa Protocol," Sustainability, vol. 16, no. 22, p. 10108, Nov. 2024, doi: 10.3390/su162210108.

[16] E. Harinda, A. J. Wixted, A.-U.-H. Qureshi, H. Larijani, and R. M. Gibson, "Performance of a Live Multi-Gateway LoRaWAN and Interference Measurement across Indoor and Outdoor Localities," Computers, vol. 11, no. 2, p. 25, Feb. 2022, doi: 10.3390/computers11020025.

[17] M. A. M. Almuhaya, W. A. Jabbar, N. Sulaiman, and S. Abdulmalek, "A Survey on LoRaWAN Technology: Recent Trends, Opportunities, Simulation Tools and Future Directions," Electronics (Basel), vol. 11, no. 1, p. 164, Jan. 2022, doi: 10.3390/electronics11010164.

[18] S. Dwi Putra, C. Olivia Sereati, and H. Sutrisno, "Design of IoT Monitoring System Based on LoRaWAN Architecture for Smart Green House," IOP Conf Ser Earth Environ Sci, vol. 1012, no. 1, p. 012090, Apr. 2022, doi: 10.1088/1755-1315/1012/1/012090.

[19] semtech, "LoRa ConnectTM 137MHz to 525MHz Long Range Low Power Transceiver."