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Original scientific paper

DESIGN AND DEVELOPMENT OF A LOW-COST ENVIRONMENTAL MONITORING SYSTEM FOR UNIVERSITY CAMPUS APPLICATIONS

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Abstract: This paper presents the design and framework development of a low-cost IoT-based multi-parameter air quality monitoring network for smart campus applications, including its hardware and software architecture and an initial evaluation of the proposed prototype. The proposed system is designed to measure key environmental parameters, including particulate matter (PM_1, $PM_{2.5}$, PM_{10}), ambient noise levels (dB), temperature and barometric pressure. The system is based on cost-effective hardware components and integrates wireless communication technologies to enable real-time data transmission. The system enables continuous monitoring while remaining user-friendly and easy to deploy. Unlike traditional monitoring systems, which rely on large and expensive equipment installed at fixed locations, the proposed system is compact and portable, allowing deployment across different locations and enabling users to monitor environmental conditions in real time, while also providing indicative insights into potential changes in measured levels. Experimental validation of the noise sensing module demonstrated good agreement with a reference sound level meter, indicating the suitability of the proposed system for indicative environmental monitoring applications.

Key words: IoT; air quality monitoring; environmental monitoring; low-cost system; wireless communication

ДИЗАЈН И РАЗВОЈ НА НИСКОБУЏЕТЕН СИСТЕМ ЗА МОНИТОРИНГ НА ЖИВОТНАТА СРЕДИНА ЗА АПЛИКАЦИИ НА УНИВЕРЗИТЕТСКИТЕ КАМПУСИ

Апстракт: Во овој труд е претставен дизајнот и развојната рамка на нискобуџетна мрежа базирана на IoT за мониторинг на повеќе параметри на квалитетот на воздухот, наменета за примена во паметен кампус, вклучувајќи ја нејзината хардверска и софтверска архитектура, како и почетна евалуација на предложениот прототип. Предложениот систем е дизајниран за мерење на клучни параметри од животната средина, вклучувајќи суспендирани честички (PM_1, $PM_{2.5}$, PM_{10}), нивоа на амбиентална бучава (dB), температура и атмосферски притисок. Системот се базира на економични хардверски компоненти и интегрира безжични комуникациски технологии со цел да се овозможи пренос на податоци во реално време. Системот овозможува континуиран мониторинг, при што останува едноставен за користење и лесен за поставување. За разлика од традиционалните мониторинг-системи, кои се базираат на голема и скапа опрема инсталирана на фиксни локации, предложениот систем е компактен и пренослив, што овозможува негово поставување на различни локации и следење на условите во животната средина во реално време, како и добивање индикативни согледувања за можни промени на измерените вредности. Експерименталната валидација на модулот за мерење бучава покажа добро совпаѓање со референтен мерач на ниво на звук, што укажува на соодветноста на предложениот систем за индикативни апликации за мониторинг на животната средина.

Клучни зборови: IoTM; мониторинг на квалитет на воздух; мониторинг на животна средина;
нискобуџетен систем; безжична комуникација

INTRODUCTION

Air pollution represents one of the major environmental challenges today, with significant impacts on human health, contributing to approximately 7 million premature deaths annually and being closely linked to respiratory and cardiovascular diseases. Skopje is frequently ranked among the most polluted cities in Europe, particularly during the winter season, when elevated concentrations of particulate matter ($PM_{2.5}$) lead to unhealthy air quality levels [1]. These conditions are mainly caused by residential heating, traffic emissions, industrial activities, and unfavorable valley topography.

Motivated by these challenges, this work presents the development of a low-cost IoT-based system for real-time monitoring of environmental parameters and air quality. The proposed system consists of an autonomous sensing unit equipped with sensors for measuring particulate matter ($PM_{2.5}$ and PM_{10}), ambient temperature, and environmental noise levels. The collected data are transmitted via LoRaWAN to a central gateway and further forwarded to a cloud-based platform for real-time visualization and analysis. The system enables continuous monitoring with periodic measurements and supports historical data analysis through graphical representations. The rapid development of IoT technologies enables cost-effective real-time monitoring and integration of multiple sensing units, contributing to more accurate environmental assessment and improved decision-making in urban environments. Several studies have proposed IoT-based environmental monitoring systems. In the study [2], a low-cost system based on Arduino UNO is presented, capable of measuring multiple environmental parameters; however, it lacks scalability and long-range communication capabilities. Similarly, [3] introduces a solar-powered system using ESP8266 and Wi-Fi communication, which is energy-efficient but limited by short-range connectivity. In [4], an ESP32-based system is proposed for real-time monitoring, but it is primarily designed for localized applications and depends on Wi-Fi communication.

In contrast, the system proposed in this work utilizes LoRaWAN communication, enabling low power, long-range data transmission suitable for distributed deployment across smart campus and urban environments. Additionally, the solution emphasizes a compact and scalable design with real time monitoring and historical data analysis capabilities.

CONCEPT FOR SENSOR NETWORK AT THE FACULTY

Proposed sensor deployment across the faculty campus

The concept of the proposed sensor network is based on the deployment of multiple distributed measurement units across our faculty campus, with the primary objective of capturing spatial variations in environmental conditions (Figure 1).

Fig. 1. Campus deployment concept of the IoT environmental monitoring system

The placement of the units is proposed based on the functional characteristics of the campus environment. Measurement units are intended to be installed at building entrances, courtyard areas, laboratory surroundings, and parking zones, where variations in air quality are expected due to human activity and localized emission sources. As a conceptual implementation, the units are proposed to be mounted on existing infrastructure elements, such as lighting poles (lamp posts), at a height of approximately 2.5 to 3 meters above ground level.

This proposed installation height is selected to approximate the human breathing zone while reducing the influence of ground level disturbances and ensuring unobstructed airflow around the sensors.

System Architecture

The system architecture is designed as a modular and distributed structure consisting of sensing, processing, communication, and visualization layers. The architecture enables continuous acquisition, preprocessing, and transmission of environmental data within a smart campus framework. The black-box model in Figure 2 illustrates the system as a functional unit that converts environmental inputs into processed and transmitted information. Inputs include ambient air parameters, electrical energy, and control signals, while outputs consist of measured data, visualized information, and transmitted signals via LoRa. The system performs acquisition, preprocessing, and communication of environmental parameters.

The functional architecture of the proposed system is illustrated in Figure 3, where the overall process is decomposed into several interconnected subsystems responsible for sensing, data acquisition, processing, communication, and visualization.

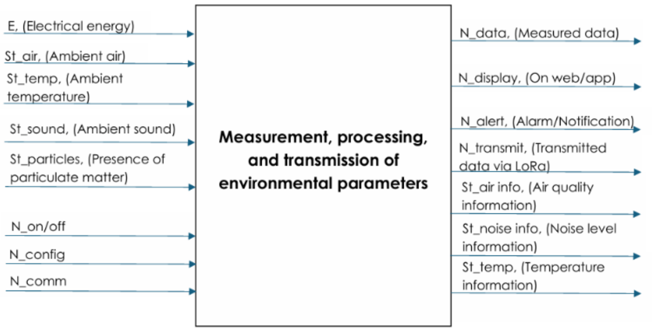


Fig. 2. Black-box model of the IoT environmental monitoring system

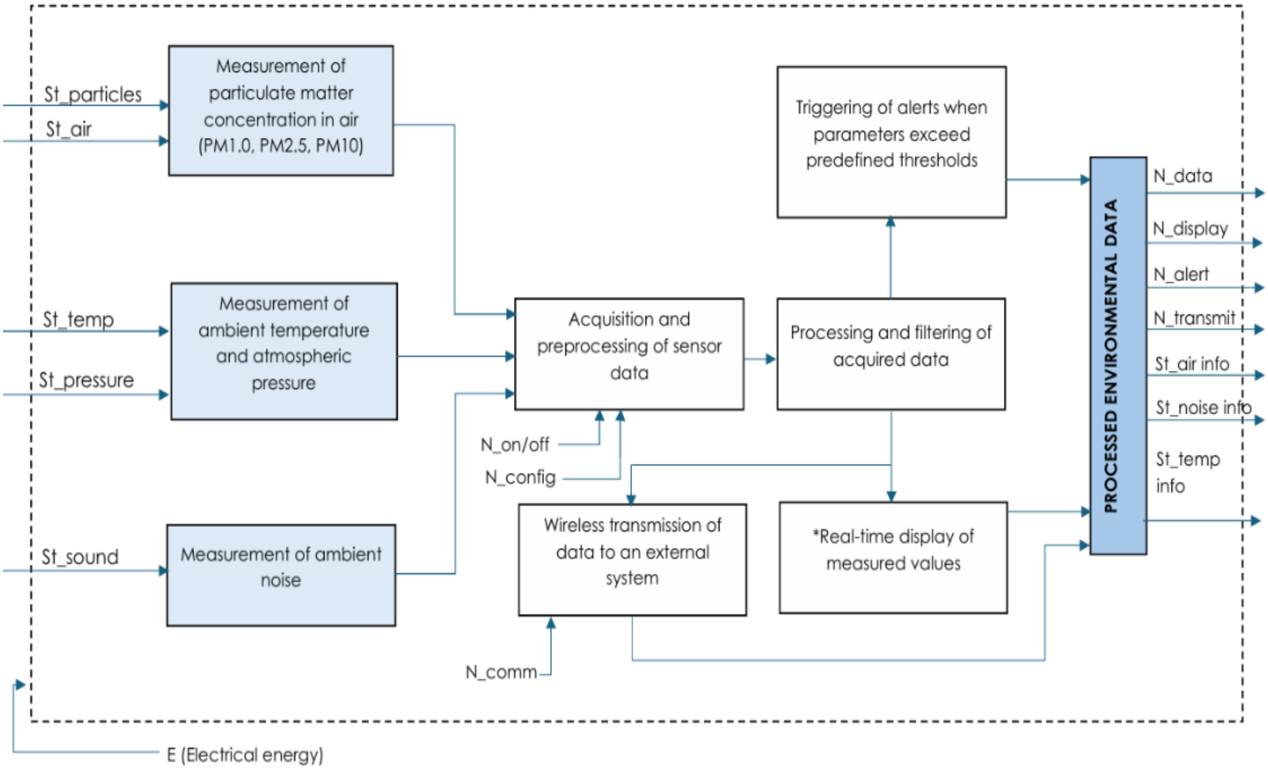


Fig. 3. Functional block diagram of the environmental monitoring system

The system begins with the sensing stage, where environmental parameters are continuously measured. This includes particulate matter concentration ($PM_{1.0}$, $PM_{2.5}$, PM_{10}), ambient temperature, atmospheric pressure, and environmental noise. These measurements represent the primary input signals to the system. The acquired sensor data are forwarded to the data acquisition and preprocessing block, where initial operations such as signal conditioning, synchronization, and formatting are performed.

Control inputs such as system configuration, communication settings, and on/off states are also processed at this stage. Following preprocessing, the data are subjected to further processing and filtering in order to improve measurement reliability and remove potential noise or outliers (Figure 4).

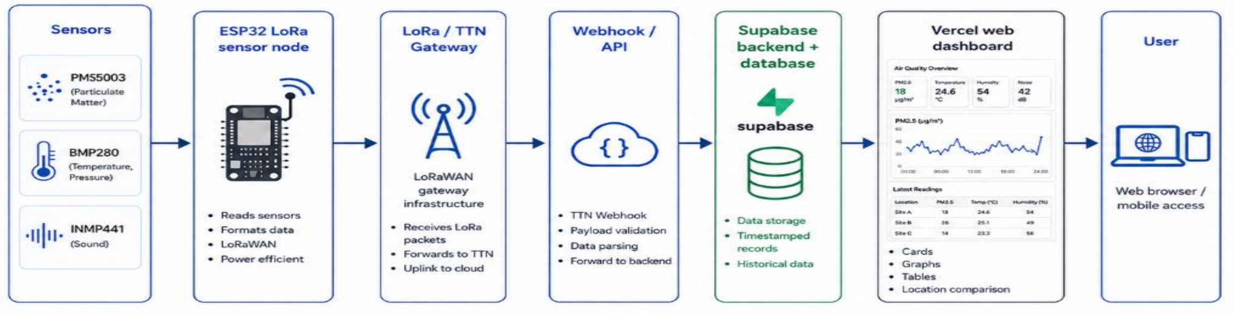


Fig. 4. Data transmission and visualization architecture using Supabase and Vercel

Based on the processed values, the system can trigger alerts when predefined threshold limits are exceeded. The processed environmental data are then directed toward two main outputs. The first output includes real-time visualization of measured values through display interfaces such as web or mobile applications. The second output involves wireless transmission of data to an external system using LoRa communication.

This modular structure enables efficient data flow, scalability, and reliable operation of the system within a distributed environmental monitoring network (Figure 5).

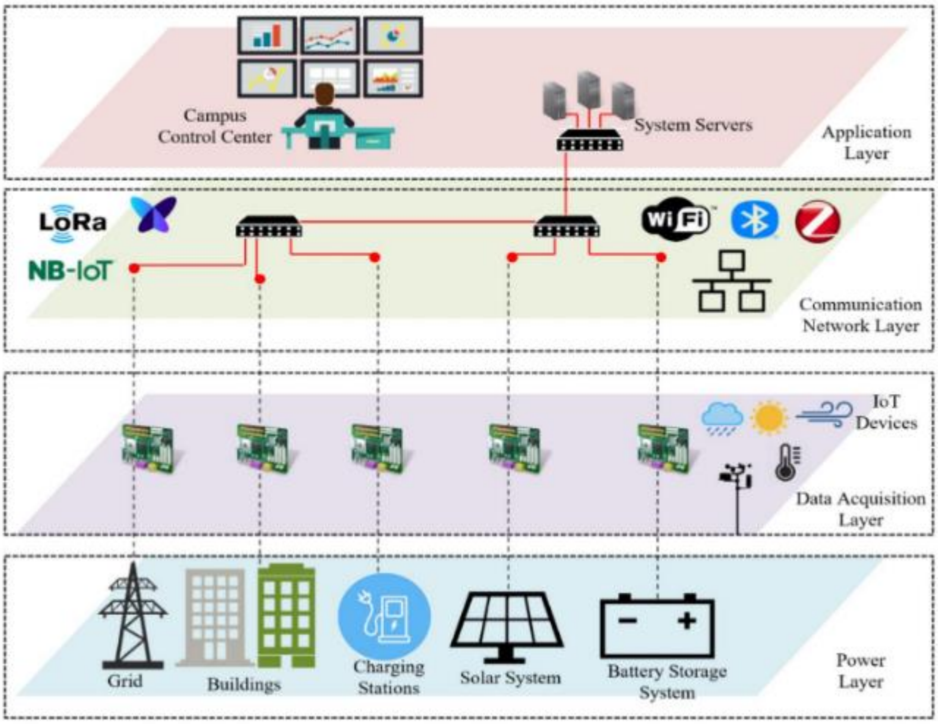


Fig. 5. Layered architecture of the proposed IoT-based environmental monitoring system

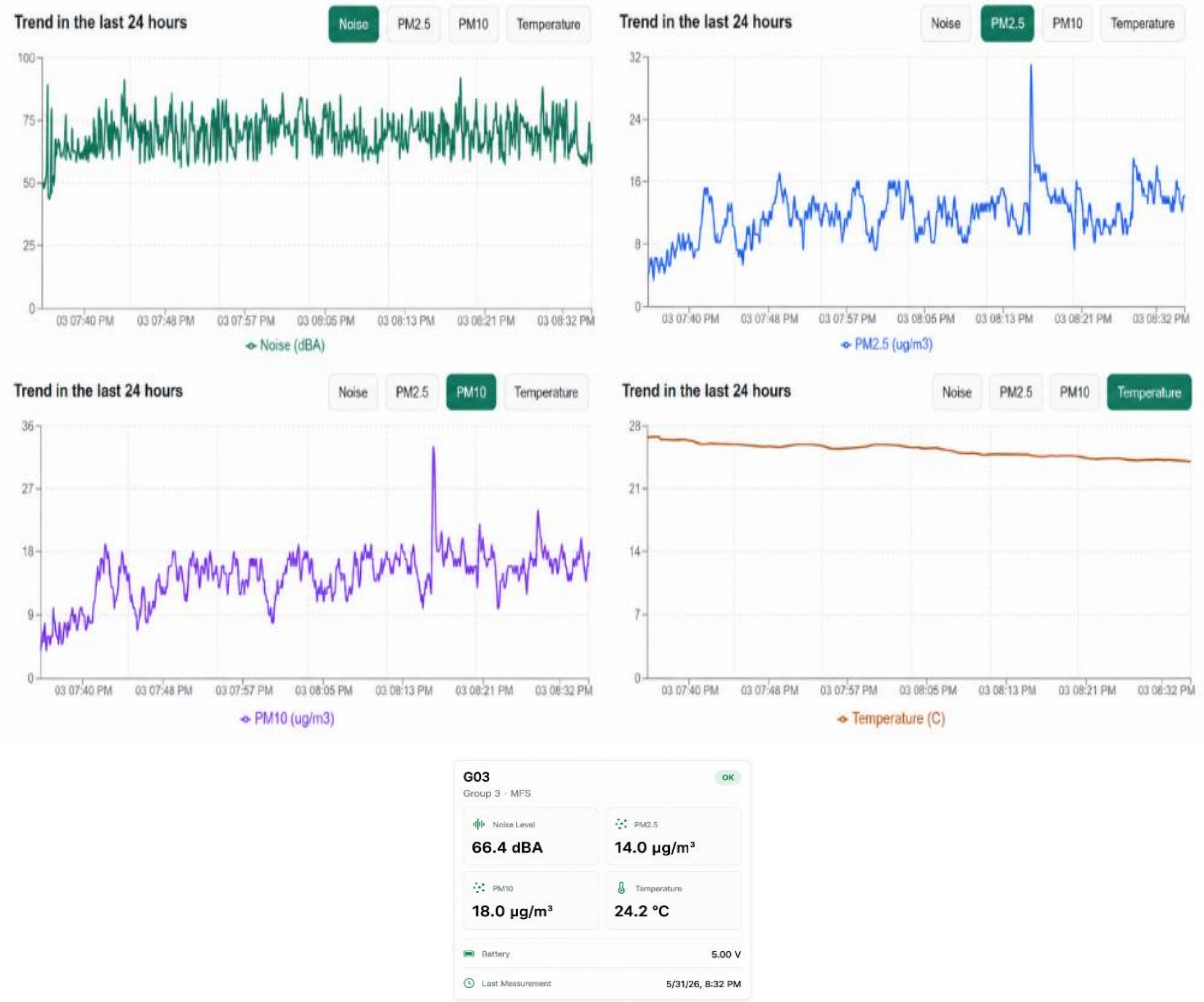
The cloud platform represents the final layer of the proposed IoT monitoring system and enables data storage, real-time visualization, and analysis of the measured environmental parameters through Supabase and a Vercel-based web dashboard [5].

After the environmental parameters are measured by the sensors, the data are processed by the ESP32 microcontroller and transmitted through the LoRa gateway. The gateway forwards the received data to the cloud backend, where the measurements are stored in a Supabase database.

Each measurement record includes the sensor node information, timestamp, and measured values such as particulate matter concentration, temperature, pressure, and noise level. This enables both real time monitoring and historical data analysis. The stored data are then accessed by a web dashboard deployed on Vercel, where the values are presented through cards, tables, and graphical representations. The platform allows users to observe current environmental conditions, analyze trends over the last 24 hours, and review daily or monthly changes. In addition, the system is designed to support comparison between different sensor nodes, which makes it suitable for future expansion into a distributed monitoring network across the university campus.

The left part in Figure 6. shows the 24-hour trend visualization of the measured environmental parameters through the web dashboard. The displayed graphs include noise level, $PM_{2.5}$ and PM_{10} particle concentrations, and ambient temperature. This visualization enables real-time monitoring and easier analysis of changes in the measured values over time. While the figure on the right shows the real-time display of the measured environmental parameters for one of the sensor nodes.

This view enables quick monitoring of the current environmental conditions at the selected location.



G03 OK
Group 3 · MFS

Noise Level
66.4 dBA

PM2.5
14.0 μg/m³

PM10
18.0 μg/m³

Temperature
24.2 °C

Battery 5.00 V

Last Measurement 5/31/26, 8:32 PM

Fig. 6. Web dashboard trend visualization of measured environmental parameters

FRAMEWORK FOR A SINGLE SENSOR UNIT

Hardware architecture

The hardware architecture of the system is based on the integration of an ESP32 microcontroller with multiple environmental sensors. The components are interconnected through standard digital interfaces, enabling reliable data acquisition and communication. The selected hardware ensures a compact, low-cost, and scalable solution.

Table 1 below summarizes the technical specifications of the sensors used in the proposed system. The selected sensors provide reliable measurements of key environmental parameters, including particulate matter, temperature, pressure, and noise levels.

Table 1

Technical specifications of the sensors used in the proposed system

Component	Parameter	Measurement method	Measuring range	Resolution/ Sensitivity	Accuracy	Interface	Supply voltage / power consumption
1. PMS5003	PM_1, $PM_{2.5}$, PM_{10}	Laser scattering principle	0 – 500 μg/m^3	1 μg/m^3	±10 μg/m^3 or ±10%	UART	5 V / ~100 mA
2. BMP280	Temperature and pressure	MEMS – based sensing	−40 to +85°C; 300–1100 hPa	0.01°C; 0.18 Pa	±1 °C; ±1 hPa	I2C	5 V / ~100 mA
3. INMP441	Sound level	MEMS digital	~30 – 120 dB (estimated)	24-bit digital output	±1 dB (typical)	I2S	3.3 V / ~0.6 mA

The PMS5003 sensor is based on a laser scattering principle and can be used for low-cost particulate matter monitoring, although its performance should be evaluated against reference instruments for reliable environmental applications [6]. The BMP280 sensor integrates temperature, and pressure measurements in a compact MEMS-based design. While the INMP441 digital microphone enables accurate acquisition of environmental noise levels.

The ESP32 LoRa module serves as the central processing and communication unit, coordinating sensor operation, managing data acquisition, and transmitting the collected data to the network gateway.

Mechanical design of the sensor unit enclosure

The mechanical design of the sensor unit enclosure was developed to provide a compact and protective housing for the electronic components and sensors (Figure 7). The enclosure is intended to be manufactured using 3D printing technology.

Fig. 7. Mechanical design of the 3D-printed sensor unit enclosure

The enclosure includes dedicated openings and internal compartments for proper sensor placement, following the design principle that particulate matter sensors require unobstructed airflow through the enclosure for reliable measurements [7]. The particulate matter sensor requires direct airflow, while the noise sensor is positioned close to an external opening in order to detect ambient sound levels more accurately. The remaining electronic components, including the ESP32 LoRa module, power management modules, and battery, are placed inside the enclosure to protect them from external influences.

The proposed enclosure design supports easy installation on existing campus infrastructure, such as lighting poles, and contributes to the portability and scalability of the monitoring system.

SOFTWARE ARCHITECTURE

Power supply concept

The proposed sensor unit is designed to operate as a portable device, suitable for outdoor placement across the faculty campus. For this reason, the power supply concept (Figure 8) is based on three possible power sources: USB power during development and testing, a rechargeable lithium battery for autonomous operation, and a solar panel for extending the operating time of the system.

Fig. 8. Power supply concept of the proposed IoT sensor unit

The selected battery is a 26650 lithium-ion cell with a nominal voltage of 3.7 V and a capacity of 5000 mAh. The battery capacity was selected based on the estimated current consumption of the main components.

The ESP32 with LoRa communication, together with the PMS5003, BMP280, and INMP441 sensors, requires a current in the range of approximately 180–250 mA during active operation. For a 5000 mAh battery, the approximate operating time can be estimated as:

$$Operating\ time \approx \frac{Battery\ capacity}{Average\ current\ consumption}$$

because the battery voltage is lower than the voltage required by some components, a power management subsystem is included. The TP4056 module is used for safe charging of the lithium battery, while the MT3608 DC-DC step-up converter is used to increase the battery voltage and provide a stable 5V supply where needed. This is especially important for components such as the PMS5003 sensor, which operates at 5V.

A 5V, 3W solar panel is included as an additional charging source to support autonomous outdoor operation, following the concept of self-sustaining LoRaWAN-based air quality monitoring prototypes [8]. The solar panel is used to support the battery charging process and extend the operating time of the sensor unit when it is placed outdoors. This makes the system more suitable for long-term environmental monitoring, since it reduces the need for frequent manual charging.

SYSTEM EVALUATION AND VALIDATION APPROACH

Noise sensor calibration and validation

The calibration and validation of the INMP441 noise sensor were performed in the mechatronics laboratory by comparing its measurements with a reference sound level meter. During the experiment, sound signals with different frequencies were generated, while the values from both the INMP441 sensor and the reference instrument were recorded simultaneously. For each frequency, three measurements were taken with the proposed sensor and three measurements with the reference instrument. The average value was then calculated in order to reduce the influence of random variations and provide a more reliable comparison between the two devices.

From the obtained graph in Figure 9, it can be observed that the INMP441 sensor follows the same trend as the reference instrument. In the graph, *Series 1* represents the INMP441 sensor, while *Series 2* represents the reference sound level meter. The sensor shows stable behavior and can be used for monitoring changes in noise level.

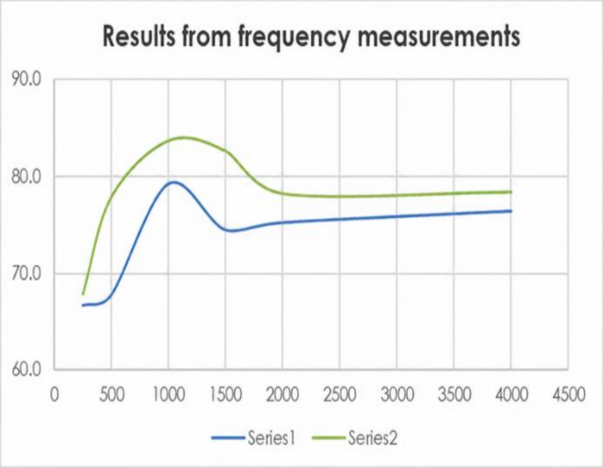


Fig. 9. Noise sensor validation at different sound frequencies

Noise sensor validation at different sound levels

Measurements were also performed at two different sound signal levels: low noise level and high noise level (Figure 10). For each level, three measurements were taken using the INMP441 sensor and three measurements using the reference sound level meter.

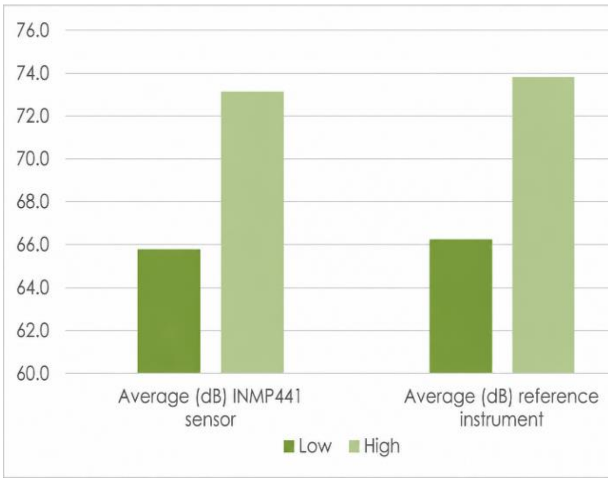


Fig. 10. Noise sensor validation at different sound levels

The average value was then calculated in order to obtain a more reliable comparison between the two devices.

Ambient noise level testing

The INMP441 sensor was also tested under ambient noise conditions in order to compare its measurements with the values obtained from the reference sound level meter.

The results showed in Figure 11 that the INMP441 sensor provides slightly lower values compared to the reference instrument. However, all measurements remain within a similar range. This indicates that the sensor can consistently detect ambient noise levels, although a certain deviation from the reference measurement is present. The observed difference may be caused by the microphone sensitivity, sensor positioning, and signal processing method.

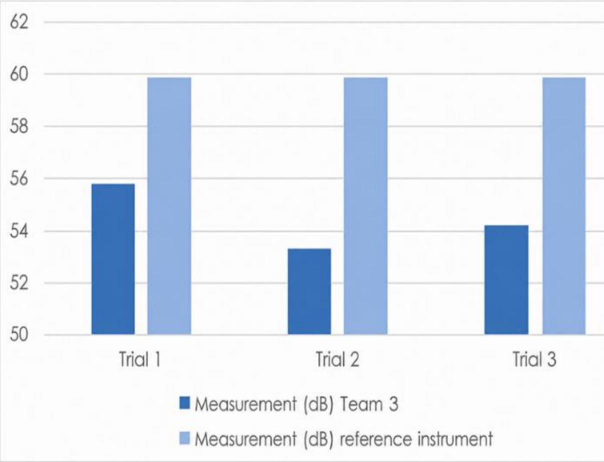


Fig. 11. Comparison of measured sound levels

The BMP280 temperature sensor would be evaluated by comparing its measurements with reference weather data or with a calibrated temperature sensor placed at the same location, following common validation approaches in which low-cost environmental sensors are assessed through simultaneous comparison with calibrated reference sensors [9]. The measurements will be performed over a defined time interval under real ambient conditions. The collected data would then be compared in order to determine whether the sensor follows the same temperature trend as the reference source. Possible deviations may occur due to local conditions such as sensor placement, airflow, shading, and the difference between point measurements and wider area weather data.

The PMS5003 sensor would be validated by comparing its $PM_{2.5}$ and PM_{10} measurements with official data from the State Automatic Ambient Air

Quality Monitoring System, operated by the Ministry of Environment and Physical Planning of the Republic of North Macedonia [10]. The sensor would be placed near an official reference monitoring station, where it would measure $PM_{2.5}$ and PM_{10} concentrations under the same ambient conditions as the reference station. The collected data would then be time aligned with the official measurements and compared in order to evaluate whether the proposed low-cost sensor follows the same trend as the reference system.

CONCLUSION

This work presented the design, development and preliminary validation of a low-cost IoT-based environmental monitoring system intended for smart campus applications. The integration of particulate matter, temperature, pressure, and noise sensors with an ESP32 LoRa module enabled real-time acquisition and wireless transmission of environmental data. The proposed cloud-based platform provided clear visualization of the measured parameters, allowing easier monitoring and analysis of environmental conditions overtime.

The developed sensor unit was designed as a modular and scalable solution, suitable for deployment at different locations across the faculty campus. The 3D-printed enclosure provided a compact housing for the electronic components while allowing proper exposure of the sensors to the surrounding environment. Testing of the noise sensor confirmed that the system follows the same general trend as the reference instrument, indicating its suitability for indicative monitoring and trend analysis.

Overall, the results highlight the effectiveness of combining low-cost sensors, wireless communication, cloud storage, and real-time visualization to create a practical environmental monitoring platform. For future work, we plan on focusing on long-term outdoor testing, further sensor calibration, power optimization, and deployment of multiple sensor nodes across the campus.

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