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Air quality monitoring system based on low power wide area network technology at public transport stops

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ABSTRACT

Mass migration from rural areas to urban areas has caused problems of traffic congestion, high industrial concentration and inequity in the distribution of housing in the world's capitals, generating a significant threat to sustainable development and public health due to air pollution air. In the Peruvian context, the importance of real-time monitoring of air quality is highlighted according to the standards established by the government. Several studies propose real-time environmental monitoring systems using internet of thing (IoT) technologies, electrochemical and optical sensors to measure pollutants, highlighting the need for data analysis. The objective of the paper is to show the implementation of IoT devices called sensor nodes, with long range wide area network (LoRaWAN) transmission technology for continuous monitoring of polluting gas concentrations. In addition, they are integrated into a central node called gateway to perform real-time monitoring through a web application. As an initial result, IoT devices demonstrated their effectiveness for real-time monitoring. Despite being a prototype-level result, the next stage involves its deployment at public transport stops in Lima. Overcoming the limitations of the solution, this paper establishes the foundation for future research on pollution and public health.

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1. INTRODUCTION

Mass migration from rural to urban areas has increased the population in capital cities of the world, where disorganized expansion has created problems of traffic congestion, high industrial concentration and inequality in the distribution of housing due to the lack of prevention in the growth of the population in underdeveloped countries [1]–[3]. The negative impact on the environment and public health due to air pollution, exacerbated by the disorderly use of transportation and the vehicle fleet, represents a significant threat to sustainable development and public health. This is a crucial problem globally, especially in low and middle income countries [4], [5] where this has generated a high emission of pollutants, such as ozone, nitrogen oxide, sulfur dioxide, carbon monoxide, and carbon dioxide [6]–[8]. Air pollution has had devastating consequences that negatively affect neurological, mental and motor development, and it is alarming that 93% of children around the world are exposed to levels of fine particulate matter 2.5 (PM2.5) above the permitted limits [9]–[11]. In the Peruvian context, air quality standards have been established according to Ministry of Environment in Peru (MINAM) [12], which define adequate levels to protect human health and well-being, highlighting the importance of real-time monitoring of air quality in urban environments [13].

Some studies propose a real-time monitoring system for environmental pollution (PM2.5 and PM10), related to respiratory and cardiovascular diseases [14]–[16]. In addition, the use of structured methodologies to investigate air quality is also described, from data acquisition to interpretation and communication, highlighting the need to analyze data in a concise manner for end users [17]–[19] using, in some cases, big data techniques [20], methodologies divided into phases to integrate internet of thing (IoT) solutions [21], [22] and transmitting information through the message queuing telemetry transport (MQTT) protocol [23]. Others researches builds prototypes of air quality monitoring stations equipped with electrochemical and optical sensors to measure pollutants such as ozone (O_3), sulfur dioxide (SO_2), carbon monoxide (CO) and particulate matter (PM) [24], [25], using free software tools, such as Python to process data [26], [27]. Furthermore, other studies have used technological advances in microelectronics to create devices capable of performing electrochemical measurements, integrating transmission techniques with global system for mobile communications/general packet radio service (GSM/GPRS) modules [28].

For these reasons, the design and implementation of an air quality monitoring and management system at public transportation stops in the city of Lima is proposed. This system uses sensors to perform real-time measurements and collect strategic information. In addition, technologies such as IoT and long range wide area network (LoRaWAN) will be used to interconnect devices and make information public. This research aims to monitor and visualize real-time data from environmental sensors in specific urban areas, with low power wide area network (LPWAN) communication and an interactive web platform. This proposal not only addresses the concern of air pollution, but also contributes significantly to the field by offering an applied technical solution. In addition, a practical and scalable approach is proposed for future implementations in other cities.

2. RESEARCH METHOD

The implementation of an IoT device, called sensor node, connected to LoRaWAN for continuous monitoring of polluting gas concentrations is conducted. To design the network that connects the sensor nodes, it is essential to know the distances to the central node, which determines the hardware and software requirements, both functional and non-functional. In terms of hardware, monitoring stations divided into five nodes and a central node called a gateway are used. Regarding the software, algorithms are used to coordinate actions for reading data sent by sensor nodes in monitoring stations, connections to a database and visualization using a web server. The diagram, shown in Figure 1, illustrates the connection of sensor nodes to the gateway through LoRaWAN, allowing the sending of information to the internet through GPRS.

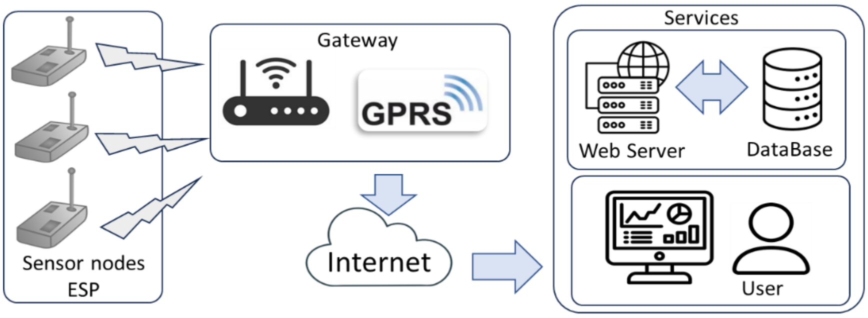


Figure 1. General scheme

2.1. System blocks

The system's hardware design is organized into four distinct blocks to optimize the development process. The sensor block collects temperature and gas data. Subsequently, the processing and control block receives the data and converts the analog signals to digital, they are processed and configured for transmission through a long range (LoRa) communications module (transmission - reception block). Finally, the packets are received wirelessly by the gateway node and then transmitted to a database via GPRS over the internet (Figure 2).

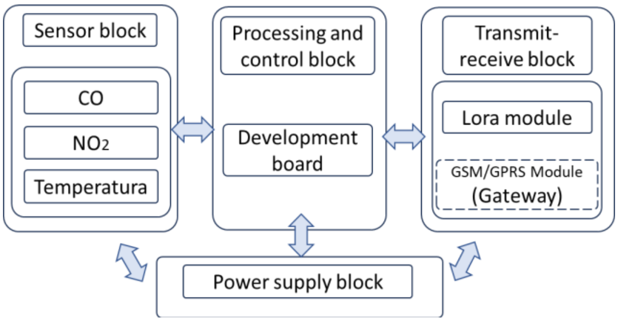


Figure 2. System blocks

2.1.1. Sensor node hardware blocks

Based on the system blocks, the technological components used to implement them were defined (Figure 3):

- The sensor block has two elements: one to monitor the levels of CO and NO_2, and another to measure temperature using an LM35 sensor (linear technology and 35 model). The CO and NO_2 module perform voltage measurements on inputs A3 for CO and input A5 for NO_2 of the Arduino module and to measure the temperature, the LM35 sensor is used.
- Processing and control block: execution of algorithms to obtain the voltage value of the LM35. Five voltage values are taken with a delay of 300 ms between each measurement. Then, the average of these 5 values is calculated and saved in the "temperature" variable, obtaining a representative value. Voltage measurements taking 10 voltage values for each gas sensor.
- Transmission – reception block: the LoRa module is integrated into the Arduino development board and its transmission module is accessed using the "LoRa.h" library to communicate with the microcontroller. To achieve this, the control pins slave select (SS), reset (RST) and DI0 are adjusted. On the other hand, the gateway node receives the information from the sensor nodes and forwards it to the GSM/GPRS module.
- Power block: it supplies power to the printed circuit board (PCB) and modules through a power supply and USB cable using a ground plane on the PCB. It contributes to more accurate sensor readings and facilitates more efficient communication with GSM/GPRS module.

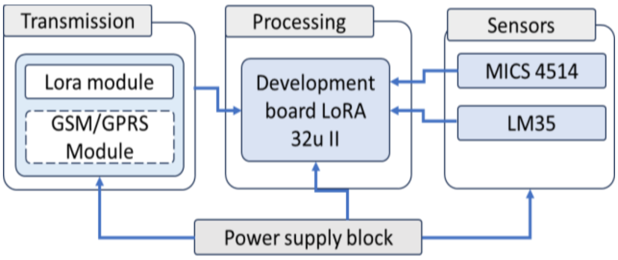


Figure 3. Hardware blocks of the sensor node

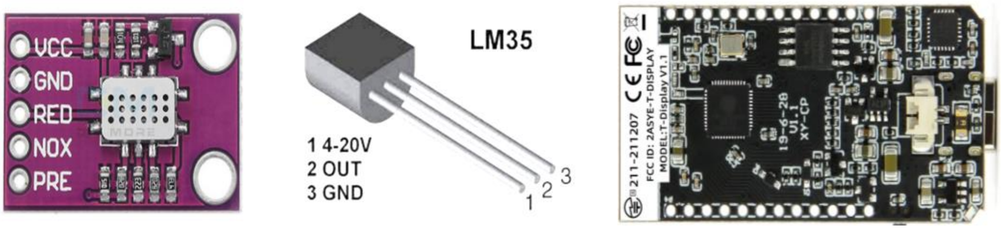
2.1.2. Sensor selection

Figure 4 shows the key components used in the project to monitor gases and temperatures using sensors and perform data communication. The Figaro brand Microsensors 4514 (MiCS 4514) sensor is used for gas reading due to its ability to measure both CO and NO_2 (Figure 4(a)), at an affordable price, thus meeting the project requirements and providing a cost-effective solution. This device meets the requirements of the project and provides a cost-effective solution that fits the objective of having a low-cost solution. For temperature, the LM35 sensor is used due to its high precision of 0.5 °C (at 25 °C) and its standard TO-92 package, which has 3 pins (Figure 4(b))

2.1.3. LoRa communication module

Several development boards were evaluated with the SX1276 LoRa chip, such as the LoRa32u II from base station (BS) France and the TTGO ESP32 LoRa (TTGO is a family of development boards and electronic modules, and ESP refers to the series of microcontrollers produced by espressif systems company) (Figure 4(c)). Both meet the necessary features for the LoRa module, but the TTGO ESP32 LoRa has additional functionalities, such as a WiFi module and an organic light-emitting diode (OLED) display, which are not necessary for this project and increase costs. Therefore, it has been decided to select the LoRa32u II board, which satisfies the LoRa module requirements efficiently and economically along with the sensors seen in Figure 4.

In the case of the GSM module, the SIM8001 offers reliable cellular connectivity and wide coverage. It takes advantage of the energy efficiency and range of the LoRa module, along with the broader connectivity and coverage provided by the GSM module. The integration of these technologies makes it possible to ensure communication in environments that require continuous connectivity.



(a) (b) (c)

Figure 4. Environmental sensor for (a) gas, (b) temperature, and (c) TTGO LoRa module

2.2. Software design

The software is present in various stages of the system. Firstly, it is responsible for collecting and sending temperature, CO, NO_2 data using LoRaWAN, storing them in a database and implementing a web application on the internet (Figure 5). Data from the sensors are used to evaluate the concentration of contaminants, averaging samples taken over at least one hour. Then, a unique LoRa message is created for each node, which is sent to the gateway that verifies the authentication through the activation by personalization (ABP) method and adds, to the payload, the database uniform resource locator (URL) and a token. Thus, a GPRS connection is established, and the data is sent to the database using the POST method (a method of sending data to the server for processing).

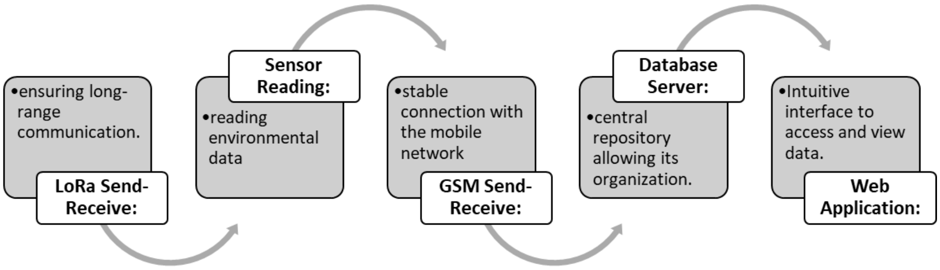


Figure 5. Software blocks

2.3. Web monitoring application

This section shows the design of the backend and frontend, detailing the technologies and components that facilitate the interaction between the server and the user. The frontend is responsible for the visual representation and graphical user interface in a web browser, involving the use of hypertext markup language (HTML), cascading style sheets (CSS) to define styling, and JavaScript to interact with users and create dynamism in the web page. The backend uses tools such as personal home page (PHP) and JavaScript to manage the site logic using tools such as cPanel and PhpMyAdmin manage the hosting and database services respectively. Three tables are used in MySQL: "data" to store sensor information with unique identifiers, "token" to validate input to "data" via POST web requests, and "users" for details of system users (Figure 6). Information acquired from the sensors will be recorded only through a validation sequence using a valid application programming interface (API) token (Figure 7).

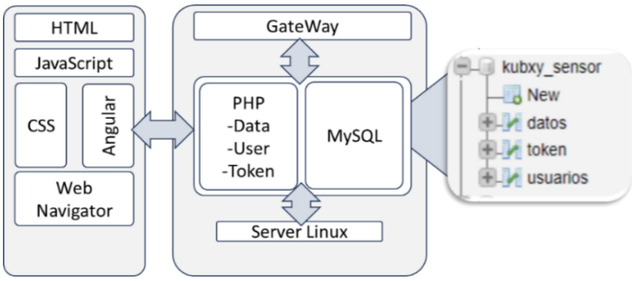


Figure 6. Web application diagram

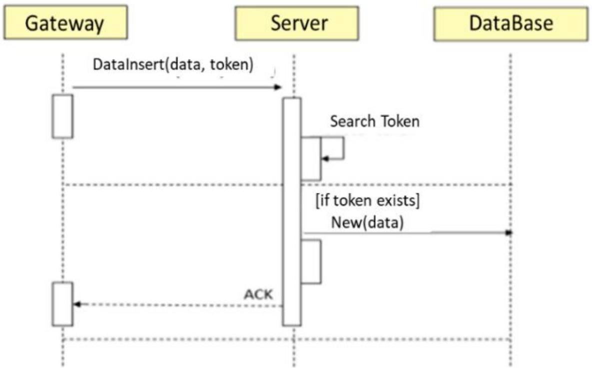
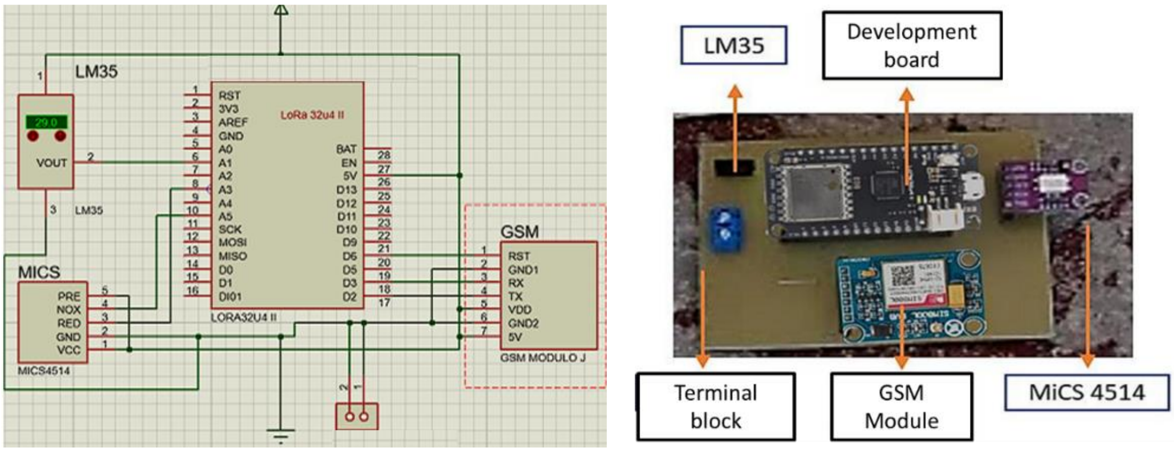


Figure 7. Insert data sequence diagram

3. RESULTS AND DISCUSSION

3.1. Prototype implementation

The initial simulation of the system nodes was carried out. This step was considered essential to verify the effectiveness of the algorithms intended to collect data and to evaluate the operation before the construction of a prototype and ensure operational consistency to finally conduct the construction of the node (Figure 8). To do this, first the schematic design and simulation of the operation of the sensor node was conducted (Figure 8 (a)) and subsequently the node was built in the implementation stage (Figure 8 (b)).



(a) (b)

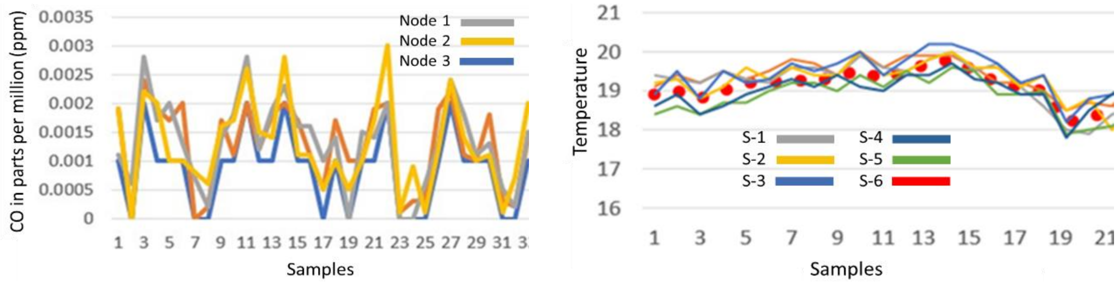
Figure 8. Sensor node in the (a) schematic design stage and (b) implementation stage

Tests were carried out to calibrate the sensor, comparing the readings with a reference device corresponding to each sensor. The calibration was validated using 50 samples taken during one hour from all sensors with 3 nodes built. Despite the variations in the measurements, the Pearson correlation coefficient was used to verify whether the data from the sensors of the nodes were linearly related to the data from the reference equipment. Table 1 shows that the calibration has been successful since there are strong and significant correlations.

Table 1. Acquired data

Sensor	Node identifier	Correlation coefficient	Average error
CO	S-1	0.94	9.91%
	S-2	0.88	11.50%
	S-3	0.87	11.12%
NO_2	S-1	0.89	8.21%
	S-2	0.82	10.2%
	S-3	0.81	9.2%
LM35	S-1	0.9	14.83
	s-2	0.87	10.12
	s-3	0.95	15.21

The results of data acquisition from nodes 1, 2 and 3 are presented in Figure 9, and show successful calibration with strong and significant correlations. CO ppm (Figure 9 (a)) and temperature measurements were made with the LM35 sensors, which showed a difference of 2 to 3 °C compared to the reference sensor (Figure 9 (b)). These differences may indicate the need to adjust the LM35 sensors to improve their accuracy and align them with a reference sensor or environmental conditions at different locations.



(a) (b)

Figure 9. Comparison of (a) CO and (b) temperature sensor data

3.2. Data transmission

To conduct data transmission, it is necessary to configure the spread factor (SF) for LoRa communication, evaluating the signal strength indicator (RSSI) and the signal-to-noise ratio (SNR) received by the gateway. In addition, evaluations were carried out of the GSM module integrated into the gateway, using a chip from the "Claro" operator. Through this communication system, internet control message protocol (ICMP) tests were conducted towards the database for 10 minutes, measuring the average latency and the percentage of packets lost with the “AT+CIPPING” command (AT is Attention and CIPPING refers to a packet internet groper functionality implemented in the modem) and recording the number of hops given by 131 packets. The procedure was repeated with chips from other operators (Entel and Movistar). The results, presented in Table 2, showed that there were no lost packets, but the mobile operator "Claro" had the lowest latency.

The data transmission tests were carried out in the laboratory, using the network nodes and it was confirmed that the information was correctly transmitted to the database on the internet. These results highlight the potential of the system and suggest that, with the amount of data generated, analysis could be performed using big data solutions, especially in studies related to climate and pollution. Figure 10 shows the data acquired for temperature and NO_2 for a period of 5 hours, recorded in the database.

Table 2. Evaluation of GPRS communication systems

Telephone operator	Average latency (ms)	Percentage of packets lost (%)	Number of data packet hops
Claro	76.27	0	16
Entel	86.64	0	19
Movistar	151.1	0	21

	id	sensor	CO	NO2	T	H
☐ Edit Copy Delete	1125	2	2030.63	17.99	14.65	
☐ Edit Copy Delete	1126	1	2057.26	20.20	15.00	
☐ Edit Copy Delete	1127	5	1096.37	20.05	14.94	
☐ Edit Copy Delete	1128	4	1997.77	20.46	16.87	
☐ Edit Copy Delete	1129	6	1105.83	20.25	17.4	
☐ Edit Copy Delete	1130	3	1934.89	20.28	14.74	

Figure 10. Data storage and visualization with the web application

4. CONCLUSION

In this paper, an IoT device, sensor node, integrated with LoraWan technology has been successfully implemented for continuous monitoring of polluting gas concentrations. This implementation is essential to understand the hardware and software requirements essential for the network design, which involves monitoring stations divided into three nodes and a central node, the gateway. Through control algorithms, the reading of data from the sensor nodes has been coordinated, establishing connections to a database and allowing visualization through a dedicated web server.

The monitoring system demonstrated its effectiveness by recording real-time data at public transportation stops in Lima. The sensors used provided precise measurements, and the web page created allowed the measurements to be displayed in a clear and understandable way, identifying patterns in air pollution over time. This tool thus becomes a valuable resource, allowing informed decisions to be made to improve the air quality and public health in the city.

Although the validated prototype worked correctly, limitations were recognized, such as interference in measurements due to environmental or technical factors. Despite this, the system offers valuable information to identify areas with high contamination and develop mitigation strategies. This research lays the foundation for future research, suggesting the need for more extensive, long-term studies to better understand pollution patterns and their impact on public health.

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