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Development of a low-cost and low-power air quality and weather monitoring system

Desarrollo de sistemas de bajo costo y bajo consumo para mediciones de calidad de aire y meteorología

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Abstract

Due to the recent pandemic, air quality monitoring has seen a resurgence of interest, however, commercial equipment for environmental monitoring needs a considerable economic effort. In this project, a prototype of a meteorological and air quality monitoring system is developed and implemented. The validation of the system was conducted by comparing the energy consumption with the Gila station, a version used previously. The system is composed of a sensor node, a gateway, and an application server. Communication between the sensor node and the gateway is through the LoRaWAN low-power protocol and The Things Network (TTN) service is used for IoT integration. The system monitored meteorological and air quality variables using low-cost components and with low energy consumption and prolong its autonomous life thanks to an energy harvesting system.

Monitoring, LoRaWAN, Air Quality, IoT

Resumen

Con la reciente pandemia, el monitoreo de la calidad del aire ha visto un resurgido interés, sin embargo, los equipos comerciales para monitoreo ambiental suponen un gran esfuerzo económico. En este proyecto se desarrolla e implementa un prototipo de sistema de monitoreo meteorológico y calidad del aire. La validación del sistema propuesto se llevó a cabo comparado el consumo energético con la estación Gila, una versión empleada con anterioridad. El sistema está compuesto por un nodo sensor, un gateway y un servidor de aplicación. La comunicación entre nodo sensor y gateway se da a través del protocolo de baja potencia LoRaWAN y se emplea el servicio The Things Network (TTN) para la integración IoT**.** El sistema probó monitorizar variables meteorológicas y de calidad del aire con componentes de bajo costo y produciendo un bajo consumo energético y prolongando su vida autónoma gracias a un sistema de recolección de energía.

Monitoreo, LoRaWAN, IoT, Calidad de Aire, IoT

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1. Introduction

Today, knowing the levels of air pollution in cities has become a factor of which it is essential to be aware of its negative impact not only on the environment but above all on health and comfort of the human being, since the presence of pollutants such as particulate matter in its 2.5 and 10 micrometer version ($PM_{2.5}$ y PM_{10}), ozone (O_3) and total suspended particulate (TSP) are related to some respiratory diseases like asthma, infections or pneumonia, cardiovascular diseases and increased mortality, especially in urban areas (Sánchez & Caraballo, 2015; Montaño *et al*., 2016).

In Mexico, atmospheric monitoring began in 1950, until 14 manual stations were incorporated in 1966 to monitor smoke, particles, and sulfur dioxide. It is not until the 70's that a manual network composed of 22 stations scattered in various cities was installed (apud Martínez & Romieu, 1997). So, until 1986 with the entry of Mexico into the GATT (General Agreement on Customs Tariffs and Trade), the Official Mexican Standards (OMS) are established following the recommendations of the International Organization for Standardization (ISO). Within these regulations, those related to the monitoring of air quality and their respective tests are those issued by the Secretariat of Health and by the Secretariat of Environment and Natural Resources (SEMARNART for its acronym in Spanish) (Instituto Nacional de Ecología, 2018).

Seeking to comply with the corresponding regulations, institutions and governments resort to the use of commercial base stations to carry out air quality monitoring. For example, Sonora State Government installed a TE-6070V manual equipment in the city of Hermosillo to monitor PST and PM_{10}associated with the lack of paving, sprawling urban growth, and vehicular traffic. (Duarte Tagles *et al*., 2021). Subsequent studies focused on the state of Sonora investigated the impact of heavy metals present in the air on health (Cruz Campas et al., 2017), finding that the presence of copper practically on every day of the experiment in the cities of Hermosillo and Obregón has a moderate to strong relationship with acute respiratory infections (ARI), while in the city of Guaymas diseases such as pneumonia-bronchopneumonia are attributed to the presence of nickel.

It should be noted that although in some cases there was the presence of metals on most days, these do not exceed the established limit, so they do not pose a problem for the health of the population. Meanwhile in his study (Cabrera *et al*., 2021) found an association between mortality from Covid-19 and exposure to NO_2 in Mexican cities.

Despite the effectiveness of manual systems, they have a series of disadvantages such as involving a great economic effort, they are large, difficult to install and maintain, the data generated is stored locally, and finally do not allow modification, therefore, the parameters of interest cannot be selected and in this particular case there is only the ability to monitor two air quality parameters and they do not keep a record of parameters such as temperature, relative humidity, wind speed and direction with which studies can be carried out looking for its relationship with air pollution or health.

Thanks to the integration of the Internet of Things (IoT) with wireless sensor networks (WSN), a wide range of applications arise such as agriculture, industrialization, environmental monitoring, vehicle tracking, buildings, smart cities intelligent, as well as security and medicine (Jino Ramson & Moni, 2017).

These networks can be developed of a few sensor nodes up to thousands of them, capable of collecting, and processing information from the environment and transmitting it either to other sensor nodes or to a base station through one or more gateways. So, taking advantage of the rise of the IoT and the easy access to a wide range of sensors and actuators have driven the community in the development of sensor networks for air quality monitoring.

Thanks to this initiative, there is a higher level of customization in terms of variables of interest and adaptability to the environment, whether they are closed spaces or outdoors, thus obtaining good performance with less economic effort.

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The remaining sections of this review article are organized as follows. Section 2 identifies the possible innovations and describes the problem to be solved, later in Section 3 the state of the art of air quality systems is presented. Section 4 describes the methodology and development of the proposal while Section 5 discusses the main results obtained, Section 6 indicates the institutions financing the work and finally Section 7 presents the conclusions and possible future work.

2. Problem

Although a series of projects have been carried out by research institutions seeking to monitor air quality in the city of Hermosillo, these systems are expensive and have not optimized their energy performance, depending largely on rechargeable batteries and using technologies such as Wi-Fi or Bluetooth for data communication.

Therefore, in this scenario, the following research questions arise: How to increase the useful life of the current meteorological stations in the city of Hermosillo? What is the impact of adding new air quality variables in terms of energy consumption?

3. Related Work

Many of the approaches or strategies for the development of a low-cost wireless sensor network or IoT system for monitoring air quality consist of using Arduino, the ESP8266 and ESP32 NodeMCU microcontrollers, or the Raspberry Pi family microcomputers as a processing unit (Abraham & Li, 2016; Ming et al., 2019; Sharma et al., 2019). Another factor in common is that they take as main parameters of interest the $PM_{2.5}$, PM_{10} O_3, CO_2 and total volatile organic compounds (TVOCs) using sensors such as MQ-135, MQ-131, CCS811, Plantower PMS5003 and PMS7003 supported by DHT22 or BME280 (temperature and humidity sensors) to carry out their calibration if necessary (Johnston *et al.*, 2018; Jose & Sasipraba, 2019; Sun *et al.*, 2017; Velasquez Garcia, 2022).

Since the outbreak of the COVID-19 pandemic within the literature, the number of articles on air quality based on wireless sensor networks has increased, (Filip *et al.*, 2020) presents an air quality monitoring system that uses a Raspberry Pi as a processing unit and monitors parameters such as $PM_{2.5}$, PM_{10}, CO, CO_2, O_3, SO_2, and TVOC's taking advantage of the LoRa network of the city of Timișoara, Romania to transmit them and later visualize them in a web interface. While (Zhou *et al.*, 2020) presents an intelligent air quality monitoring system that uses an Arduino Leonardo with LoRaWAN modules to communicate with the LoRa platform "The Thing Networks" (TTN) which integrates with Ubidots, an IoT platform for data analysis, visualization and sending SMS alerts when the parameters are not within the established threshold.

Likewise, in the work developed by (Glass *et al*., 2020) a monitoring system for air quality of a compact design is described again, with integration to the cloud and with the addition of operating on solar energy. Meanwhile, the design of the Energy Harvesting System (EHS) is hardly detailed and the analysis of energy consumption and loading and unloading time is left for future work.

Unlike the works already mentioned (Sampaio et al., 2019) tested its system with three different transmission media, Zigbee, Xbee antennas with Wi-Fi, and BLE with low-cost sensors such as MQ-2 and DHT11, it performed an analysis of the entire system from the work cycle of the sensors, the current per hour in mA of each sensor, of the Arduino in active and idle mode and the modules in their respective states. While (Babatunde et al., 2020) presents an air quality monitoring system whose central node unit is an MSP430FR5969 development card that interprets the CCS811 sensor values in carbon dioxide equivalent (eCO_2) and volatile organic compounds. (TVOC's) and thanks to a LoRa SX1276 radio it communicates these parameters within a coverage area of up to 1km in a direct line of sight. The system harnesses solar energy through a cell and ceramic capacitors to power the system. Although the MSP430FR5969 was chosen for its low energy consumption, some tests were carried out with an Arduino, because when trying to make the first development board work, problems were found.

After all, instead of providing 3.3V, 1.9V was obtained, which made it impossible the operation of LoRa radios.

However, among the works oriented to low-cost or low-power systems (Abraham & Li, Op. Cit.) implemented a low-cost indoor air quality monitoring system taking an Arduino as a processing unit, the system uses Xbee modules (implement Zigbee) in a mesh-type topology to support system communication, the results obtained were validated by comparing them with a trading system (GrayWolf System). However, this work, being focused on indoor monitoring, uses a cellular technology such as Zigbee, which does not have great coverage and although the components used are accessible to most of the community, its energy impact on the system was not described. Meanwhile, (Hossein *et al*., 2020) developed two generations of portable device that has a Wi-Fi module and a cell phone that provides GPS for the recording and visualization of particulate matter and meteorological variables such as temperature, humidity, and pressure. The presented device can be powered either from the power outlets or via a portable charging module, although they do not communicate with each other and the need for a cell phone hinders the scalability of a possible network made up of these devices, consequently these factors make it unfeasible due to the high economic cost that it would entail.

(Kortoçi *et al*., 2022) presents a portable low-cost sensor device to measure air quality in the districts of Pakila and Pirkkola Finland, with this device it was sought not to depend on static stations and thus be able to identify the areas of greatest contamination taking into account closed spaces (buildings) and open spaces (environment) identifying these types of spaces by their temperature and taking 20°C as a delimiter. Thanks to an accelerometer, the device differentiates between two states (movement and rest) to adjust the sampling period and thus save energy. Although the developed device was compact, facilitating its transport and portability, it was somewhat fragile, consequently presenting problems to the subjects who carried out the study, since the device fell or was hit, the sensors were broken or desoldered, respectively, and the calibration process of the sensors was not described either and the main drawback is that you need a cell phone to record the data via BLE (Bluetooth Low Energy).

(Abdaoui *et al*., 2020), conducted an outdoor air quality monitoring system capable of measuring the concentrations of CO2, CO, and Cl2 as well as meteorological variables such as temperature, pressure, and relative humidity. The system is made up of a sensor node that transmits the information from the calibrated sensors via Xbee to a Raspberry Pi microcomputer used as a Gateway.

Regarding the power supply of the system, it was decided to take advantage of solar energy, for which a 5V-2W photovoltaic panel was used, and to determine the energy efficiency, two rechargeable lithium-ion batteries of 2300 and 6600 mAh were used to estimate the rate loading and unloading; selecting the 6600 mAh battery as it showed 12% consumption during discharge.

Although in this work the energy aspects of the system are detailed and its architecture is illustrated, the calibration process of the sensors is not detailed.

On the other hand, (Sampietro-Saquicela *et al*., 2022) describes a series of metrics with which to validate the installation of an air quality monitoring system in the city of Esmeraldas in Ecuador from an economic perspective, within these metrics the environmental impact is listed (data of air quality, energy consumption, regulation by control bodies, etc.), technological impact (reliable, innovative, technical solution, software, and hardware upgradeability, etc.) and finally the economic impact considering the cost of components and supplies, labor and payment to professionals, as well as the annual investment.

Table 1 summarizes the characteristics of some of the previous systems with the addition of the "Gila" meteorological and air quality station, developed by (Grijalva *et al*., 2022) in a proposal before the development of this project.

This system is capable of monitoring temperature, relative humidity, atmospheric pressure and concentration of $PM_{2.5}$ and PM_{10} in 0.01cubic feet (ft^3) through an ESP8266 NodeMCU.

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	Parameters	MCU	Protocol	EHS
Abraham	O_3, CO, CO_2, TVOC's	Arduino	Xbee	No
Sampaio	CO_2, Co, Cl_2	Waspmote	Xbee	Yes
Hossein	PM, T, HR, P	NA	Wi-Fi	No
Glass	CO, NO_2, PM	Murata	LoRa	Yes
Babatunde	eCO_2, TVOC	MSP430	LoRa	Yes
Gila	T, RH, PM.	ESP8266	Wi-Fi	Yes

Table 1 State of the art systems comparison.
Source: Developed by the authors based on the works of (Abraham & Li, 2016; Sampaio et al., 2019; Hossein et al., 2020; Glass et al., 2020; Babatunde et al., 2020; Grijalva et al., 2022)

4. Proposed System Design

This work focuses on the development of low energy consumption and low-cost system capable of monitoring meteorological (temperature, relative humidity, atmospheric pressure) and air quality parameters (carbon dioxide, carbon monoxide, ozone, and particulate matter).

Figure 1 shows the block diagram of the architecture of the proposed system, which has a sensor node that is powered by an EHS and establishes communication with the Gateway through LoRaWAN. In turn, via Wi-Fi, Ethernet, or 3G, it communicates with The Things Network, a global LoRaWAN network server.

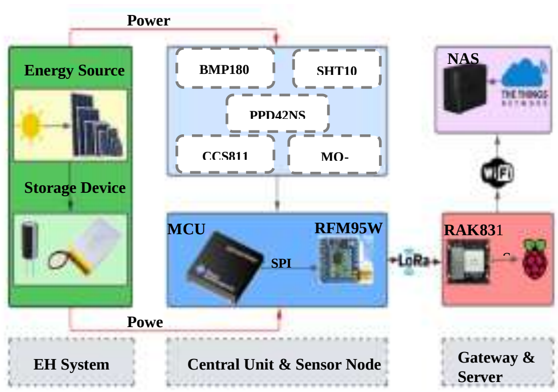


Figure 1 Proposed system block diagram
Source: Own Elaboration

1.1. Sensor Node

The sensor node designed is not only capable of monitoring air quality variables such as ozone (in ppm), particulate matter in its variants $PM_{2.5}$ y PM_{10} ($\frac{\mu g}{m^3}$), carbon dioxide (in ppm) and TVOC's, if not also monitor environmental parameters such as temperature (°C), relative humidity (%) and atmospheric pressure (hPa).

It establishes communication with the gateway thanks to LoRa modules using the 915MHz frequency band and has a program that interprets the signals from each sensor, starts the transmission of packets, and optimizes energy consumption.

During the selection of the central unit from the sensor node, energy efficiency was prioritized over the popularity of the device, so the MSP-EXP430FR5969 microcontroller from the Texas Instruments MSP430 family, characterized by its ultra-low power consumption, was chosen. The open-source platform "Energia" is used to upload the codes in to the microcontroller, meanwhile most of the sensor selected are well known and easy to acquire. The components that conform the sensor node are specified in Table 2.

Component	Function	Cost (mxn)
MSP430	Processing	541.5
SHT10	T and RH reading.	979
BMP180	T and P reading.	26
CCS811	eCO_2 and TVOC reading.	470
PPD42NS	$PM_{2.5}, PM_{10}$ measure.	249
MQ-131	O_3 reading	780
RMF95W	LoRaWAN access.	390.6
Total		3436.1

Table 2 Sensor node components
Source: Own Elaboration

1.2. Gateway

To receive the packets sent by the sensor node, the RAK831 concentrator module was chosen. This module is designed for IoT, Smart Sensing, and M2M (Machine-to-Machine) applications and to receive multiple LoRa packets simultaneously using different spreading factors (SF) on multiple channels.

The RAK831 module is accompanied by a Raspberry Pi 3B+ microcomputer as a host, which has the necessary firmware for the module to establish the connection with the external server of The Things Network (TTN) through an Activation By Personalization (ABP) where the device address and session keys are predefined so they do not need to be re-negotiated when starting a new session.

1.3. Server

The core of the server is a NAS (Network Attached Storage) unit, which is an intelligent storage device connected to a local network. The version of the NAS used has 34 TB of space in which the data received when subscribing to the MQTT topics provided by TTN is stored and with the possibility of hosting a web server for viewing and downloading data and issuing alerts. The data flow diagram between the gateway and the server can be seen in Figure 2.

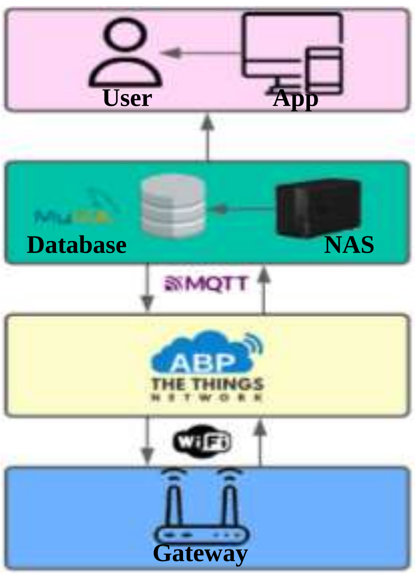


Figure 2 Gateway-Server Data flow
Source: Own Elaboration

1.4. Energy Harvesting System

Among all the sources from which it is possible to collect energy in the State of Sonora, the most feasible options are solar and wind energy, however, these depend largely on the application and the conditions of the region, for example, although solar energy is unlimited, it is not always present (during cloudy periods or night) and is diminished if it is not outdoors or due to lack of maintenance on the solar panels (dirt, damage from rain or animals). Even so, solar energy is chosen to provide energy support to the monitoring system.

To collect it, there is a 20W photovoltaic panel, and a charge regulator to adjust the power to one suitable for the system. As for the technologies to store the energy produced by the EHS, supercapacitors and rechargeable batteries are the selection.

A supercapacitor has a high cycle efficiency, a large number of charge cycles, and a faster discharge time, as well as a longer life while rechargeable batteries on the other hand are used due to their high energy density, which indicates the maximum amount of energy per kilo that can be stored (Prauzek et al., 2018).

2. Results

This section first details the parameters of the LoRaWAN configuration used and then the energy consumption of each component of the sensor node and the total energy expenditure of what a work cycle would entail where the data is processed and transmitted to the sensor is estimated. server. This amount of energy consumed will serve as a point of comparison with the Gila station and above all as a guideline in the design of the energy harvesting system.

2.1. System Configuration

Before estimating the energetic parameters of the station, the metrics for the transmission of the packets containing the data of each sensor were determined. One of the most important of these metrics is time on air (ToA). The ToA is the range of time in which the packet is sent until it is received and is the sum of the duration of the preamble and the duration of the payload. (SEMTECH, 2020).

$$\mathrm{ToA} = \mathrm{T_{preamble}} + \mathrm{T_{payload}} \quad (1)$$

$$\mathrm{T_{preamble}} = \left(\mathrm{n_{preamble}} + 4.25\right)\mathrm{T_s} \quad (2)$$

$$\mathrm{T_s} = \frac{2^{\mathrm{SF}}}{\mathrm{BW}} \quad (3)$$

$$\mathrm{T_{payload}} = \mathrm{n_{payload}} \cdot \mathrm{T_s} \quad (4)$$

$$\alpha = \left\lceil \frac{8\mathrm{PL} - 4\mathrm{SF} + 28 + 16\mathrm{CRC} - 20\mathrm{IH}}{4(\mathrm{SF} - 2\mathrm{DE})} \right\rceil \quad (5)$$

$$\mathrm{n_{payload}} = 8 + \max(\alpha(\mathrm{CR} + 4),\ 0) \quad (6)$$

where:
$\mathrm{n_{preamble}} = 8$
$\mathrm{PL} \in \{1,2,\dots,255\}$ bytes.
$\mathrm{SF(Spreading\ Factor)} \in \{7,\dots,12\}$
$\mathrm{CRC} = 1$
$\mathrm{IH} = 1$ if header present, 0 otherwise
DE = 1 if $\mathrm{T_s} > 16$ ms ($\mathrm{SF} \geq 11$), 0 otherwise.
CR where $\{1,2,3,4\}$ represents $\left\{\frac{4}{5},\frac{4}{6},\frac{4}{7},\frac{4}{8}\right\}$.

So, the higher the ToA of the station, the higher the energy consumed by the sensor node. Table 3 shows the different ToA for a 16 bytes payload, at a frequency of 125kHz, a code rate (CR) of 1 and a header present.

SF	ToA (ms)
7	51.456
8	92.672
9	164.864
10	329.728
11	659.456
12	1318.912

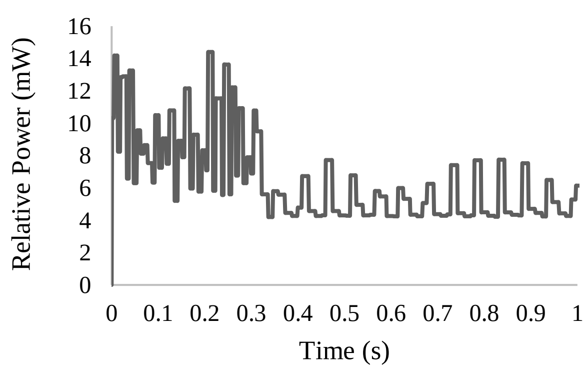
Table 3 ToA of a 16 bytes packet
Source: Own Elaboration

In the other hand The Things Network Fair Access Policy limits the uplink message to 30 seconds per day per end node, so using the previous configuration the system is able to send 22 to 583 uplink messages.

2.2. Sensor Node Energy Performance Evaluation

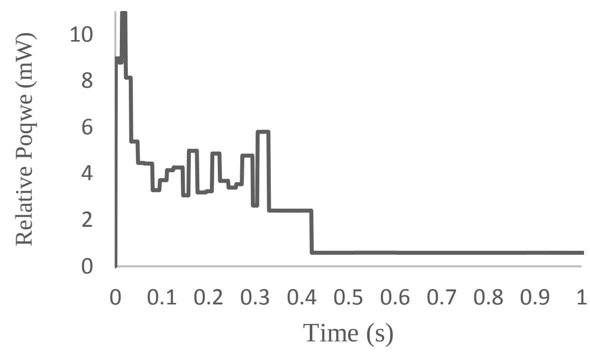
The energy analysis of the sensor node was carried out through the integrated tool in one of the development environments (Code Composer Studio) used for programming the development card: EnergyTrace™.

Communication with this tool is possible thanks to the ez-FET debugger of the card and it allows graphical visualization of the energy consumption, the active components, and peripherals in each low consumption mode (LPM) of the card. It also displays tables indicating the average, minimum and maximum energy, current, and voltage. Graph 1 shows the energy consumed by the BMP180 sensor in one duty cycle. However, it was observed that the consumption was not as low as expected.



Graphic 1 Unoptimized energy consumption
Source: Own Elaboration.

The undesirable consumption was caused due unused ports pin were unconfigured as a I/O function so it was necessary configure them as an output consequently left them unconnected on the board avoiding unnecessary extra current draw. Graphic 2 shows the impact on energy consumption configuring unused ports.



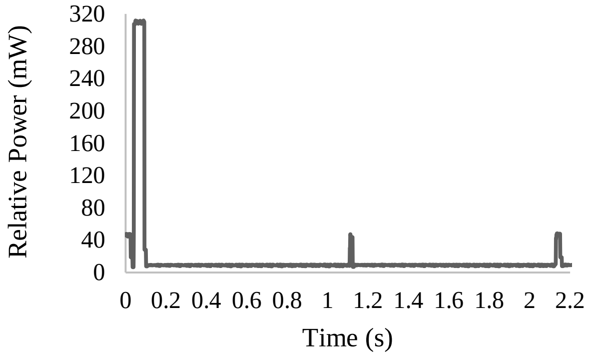
Graphic 2 Optimized energy consumption
Source: Own Elaboration

To determine the total consumption of the sensor node, the card with each sensor and module was evaluated independently, focusing on the current consumed and the operating time. These data are displayed in Table 4.

Component	Voltage (V)	Current (mA)	Time (s)
BMP180	3.6	1.096	0.336
SHT10	3.6	0.5697	1.750
CCS811	3.6	17.2729	4.1
PPD42NS	5	90	1.448
MQ-131	3.6	72.2245	15
RFM95W	3.6	5.0016	2.17

Table 4 Components energy consumption.
Source: Own Elaboration

On the other hand, the RFM95W transceiver module transmits a 16-byte packet containing the data from each sensor, with a spreading factor of 7 (SF7) over the 125kHz frequency band. Graphic 3 shows the consumption of the module and the behavior of a Class A LoRa device can be denoted, that is, the device is activated, transmits a packet, and opens two data reception windows. In this case, the transmission stage took approximately 75 ms with constant consumption of 86.9893 mA.



Graphic 3 LoRa module power consumption
Source: Own Elaboration

Once the energy consumption of each component is known separately, the total consumption of the sensor node is given by (7).

$$E_T = \sum_i^n I_i \cdot t_i \cdot V_i \quad (7)$$

where:
I = Average current.
V = Source voltage.
t = Active time.
n = # of components.
$i \in \{1, 2, \ldots, n\}$

Obtaining a total of 4.85 J (approx. 195 mW), meanwhile, testing the Gila system, it was found that it had a constant consumption of approximately 141 mA (see Figure 3), although the station takes measurements in periods of 10 minutes, due to the lack of optimization never enters into a low power mode, consequently the peripherals always maintain a constant power draw.

Figure 3 Gila station power consumption
Source: Own Elaboration
.

Then, assuming that we have the 25-second work cycle of the developed station and that it is powered by 5 V, the Gila station would consume approximately 17.625 J (705 mW), thus requiring 3.6 times the consumption of the developed station in this work.

6. Thanks

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7. Conclusions

This paper describes the design process of a low-energy meteorological and air quality station with a budget of less than 180 dollars (3436 mxn) showing an energy optimization compared to the Gila station, which approximately quadruples energy consumption even with a smaller amount monitored parameters.

Both the hardware and software technologies integrated in the sensor nodes and the gateway facilitate the creation and scalability of a network made up of the designed sensor nodes, also the importance of the correct selection of the transmission parameters over time was noted.

As future work, it is expected to implement an adequate energy harvesting system that serves as support, add new meteorological variables such as wind speed and direction, precipitation, and solar irradiation, as well as carry out exhaustive field tests with which to validate the monitored parameters.

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