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DESIGN AND EVALUATION OF A LORA ARCHITECTURE FOR MULTIPARAMETER WATER MONITORING WITH LIMITED CONNECTIVITY

**DISEÑO Y EVALUACIÓN DE UNA ARQUITECTURA LORA
PARA MONITOREO MULTIPARAMÉTRICO DEL AGUA CON
CONECTIVIDAD LIMITADA**

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Design and Evaluation of a LoRa Architecture for Multiparameter Water Monitoring with Limited Connectivity

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ABSTRACT

This article describes the design and functional evaluation of a point-to-point LoRa architecture for multiparameter water monitoring in environments with limited connectivity. An ESP32 node connected to turbidity, temperature, and distance sensors transmits independent encrypted messages to a Raspberry Pi station, which processes the data in Python and stores them in MariaDB. The evaluation combined software checks using synthetic data with a preliminary communication test at approximately 50 m, followed by a temporary installation with an estimated separation of 35 m and physical obstacles, where reception was restored after repositioning the antenna and sealing its outlet from the enclosure. The console excerpt examined showed five complete cycles, equivalent to 15 readable messages, while complementary checks reviewed the conversion of readings through calibration tables. The results support the functional integration of acquisition, communication, and local processing under the conditions examined and show that antenna placement affects link operation, although the scope of the tests does not establish the maximum communication range, overall packet loss, or the metrological accuracy of the sensors.

Keywords: LoRa communication, multiparameter monitoring, water quality, embedded systems, local processing

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Diseño y evaluación de una arquitectura LoRa para monitoreo multiparamétrico del agua con conectividad limitada

RESUMEN

El presente artículo describe el diseño y la evaluación funcional de una arquitectura LoRa punto a punto para el monitoreo multiparamétrico del agua en entornos con conectividad limitada, mediante un nodo ESP32 conectado a sensores de turbidez, temperatura y distancia que transmite mensajes independientes cifrados hacia una estación Raspberry Pi, encargada del procesamiento en Python y almacenamiento en MariaDB. La evaluación combinó comprobaciones de software con datos sintéticos y una prueba preliminar de comunicación a aproximadamente 50 m, seguida de una instalación temporal con separación estimada de 35 m y obstáculos físicos, donde la recepción se restableció después de modificar la posición de la antena y sellar su salida del gabinete. Como evidencia de funcionamiento, el fragmento de consola examinado presentó cinco ciclos completos, equivalentes a 15 mensajes legibles, mientras que las comprobaciones complementarias revisaron la conversión de lecturas mediante tablas de calibración. Los resultados respaldan la integración funcional de adquisición, comunicación y procesamiento local bajo las condiciones examinadas, y muestran que el montaje de la antena interviene en la operación del enlace, aunque el alcance de las pruebas no permite determinar su distancia máxima, la pérdida global de paquetes ni la precisión metrológica de los sensores.

Palabras clave: comunicación LoRa, monitoreo multiparamétrico, calidad del agua, sistemas embebidos, procesamiento local

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INTRODUCTION

Monitoring water-related variables requires readings to be transferred from the measurement points to a unit where they can be processed and accessed, making communication between devices necessary to keep the information available. When sensors are located in areas without access to a conventional network, surrounded by tanks, structures, or vegetation, the design must account for both the separation between the nodes and the physical conditions of the installation.

Several studies have addressed this need through sensors and monitoring platforms, including the work of Forhad et al. (2024), who integrated instrumentation, a programmable logic controller, and cloud services to record water parameters at treatment facilities. Their proposal connects data acquisition with remote access and historical recording, although it requires an infrastructure different from that considered in an architecture where processing and basic data access remain within a local station.

LoRa communication also has precedents in this field, including the system developed by Silva Torres and Coello Hurtado (2020) to monitor temperature, turbidity, dissolved solids, and pH through LoRaWAN, and the implementation by Jabbar et al. (2024), which connects a sensor node to a gateway and internet platforms to monitor water variables in rural areas. These studies illustrate different ways of organizing data acquisition and transmission, depending on the available resources and the services that must remain accessible during operation.

Pires and Gomes (2024) developed a system that transmits temperature, pH, conductivity, and turbidity readings through LoRa to a station with local processing and Node-RED visualization, with the option of also sending the data to the cloud. For river water level monitoring, Kabi, wa Maina, Mharakurwa, and Mathenge (2023) used ultrasonic sensors and examined coverage through RSSI and SNR records collected at different locations. These studies provide a basis for considering how processing is organized and how communication conditions affect the proposed system.

To describe the proposal, LoRa must be distinguished from LoRaWAN: the former is the technology used at the physical layer to transmit the radio signal, whereas the latter incorporates functions and components for managing a device network (Baltuille, 2023). The architecture developed in this study establishes point-to-point communication between the transmitting node and the receiving station, without a LoRaWAN gateway or network server.

The system integrates an ESP32 connected to three sensors and a Raspberry Pi that receives the messages, applies the configured conversions, and manages the information through a local application, so communication between the devices and basic access to the readings do not depend on internet access. This arrangement addresses the need to connect a measurement point to a supervision area while keeping processing and storage within the facility.

The objective of this article is therefore to describe the design and evaluate the functional integration of a point-to-point LoRa architecture for multiparameter water monitoring under limited-connectivity conditions, focusing on message organization, link installation, and the path followed by the readings through processing and visualization. Calibration checks provide complementary evidence of data conversion within the scope of the documented tests.

METHODOLOGY

Research approach and organization

The research followed a quantitative and applied approach directed toward the development of a monitoring system consisting of hardware and software. Its evaluation drew on the count of documented messages, processing checks, and readings used during sensor adjustment, within a technological case study that included development tests and a temporary installation in an operational water treatment environment.

The units of observation comprised individual messages, transmission sequences, and executions of the selected test cases, whose records were analyzed descriptively to determine whether the components completed the expected data path. The results were interpreted within the documented executions, without extrapolating performance rates to extended periods or installations with different characteristics.

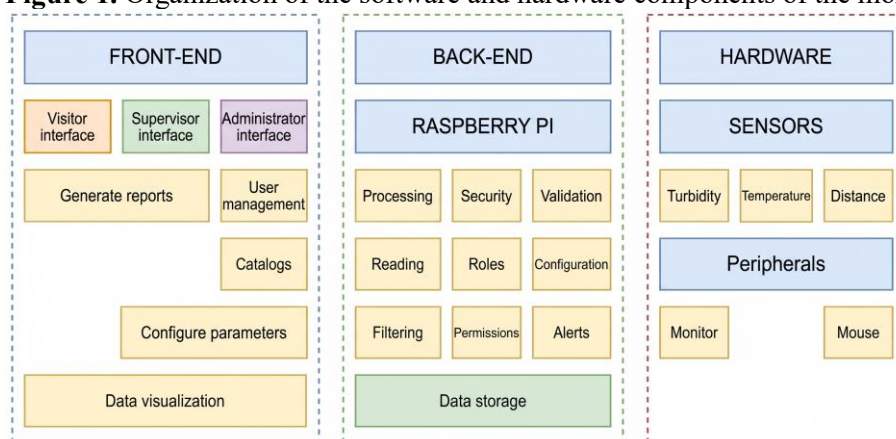
Development was organized through an adaptation of Scrum to distribute the functions into work increments, drawing on the iterative and incremental approach described by Schwaber and Sutherland (2020). Verification followed the relationship between requirements and tests established by the V-Model, covering components, integration, application functions, and complete system operation. This article primarily considers the cases associated with acquisition, LoRa reception, persistence, calibration, and the complete data path because of their direct relationship with the architecture being

evaluated.

General system architecture

The architecture consists of an ESP32-based acquisition node and a Raspberry Pi 5-based receiving station, connected through Ra-02 modules with SX1278 transceivers. The node gathers sensor readings and transmits them sequentially, while the station interprets the messages and performs local processing, following the organization of software and hardware components shown in Figure 1.

Figure 1. Organization of the software and hardware components of the monitoring system



Note. The diagram groups the system's interface, local processing, and hardware components. Source: Own work.

A desktop application developed in Python manages reception, calibrations, and the visualization of variables, while a local MariaDB database stores records for subsequent access through the system's available functions. The application also includes threshold alerts, report generation, and access control, which support supervision of the readings without being the main focus of the communication analysis. Communication between the nodes and basic data access do not require an internet connection. A Telegram notification module, however, depends on an available connection at the receiving station when that function is enabled, so independence from the internet refers to the local path of acquisition, reception, processing, and access under the equipment's operating conditions.

Acquisition and identification of variables

The TS-300B sensor provides the analog signal associated with turbidity, from which the ESP32 calculates the average of ten analog-to-digital converter readings and transmits the raw value under the N2 identifier. The Raspberry Pi subsequently converts this value using the active calibration table, so the received message and the reading displayed by the application belong to different processing stages.

Temperature is acquired with a DS18B20 through the OneWire interface and transmitted as N4, provided that the program does not detect a sensor disconnection, in which case it omits the reading. This variable was included as an additional parameter of the prototype, allowing its acquisition, transmission, and presentation to be checked within the same architecture.

The JSN-SR04T measures the distance to the water surface and transmits valid readings as N1, after which the application relates the distance to a reference level and applies a level-to-flow lookup table to estimate the flow rate. This procedure depends on the hydraulic relationship configured for the installation, since the sensor measures distance and the flow estimate is calculated later from the points recorded in the system.

Transmission organization

Each message contains a variable identifier and its value, placed in a 16-byte block and encrypted using AES-128 before transmission through LoRa. The receiving station recovers the contents for interpretation, and the functional encryption check verifies that the original identifier and value can be recovered without changes.

The expected sequence is N1, N2, and N4, with 200 ms pauses between transmissions and a base waiting time of five seconds at the end of each cycle. Acquisition and transmission times must also be included, so the programmed waiting time alone does not represent the full interval between consecutive readings of the same variable.

Messages are received independently, allowing the station to process the variables that arrive even when a sequence remains incomplete. The implemented protocol does not include sequence numbers, reception acknowledgments, or automatic retransmissions; because the program may also omit readings that do not meet its validity conditions, a missing identifier in the console cannot, by itself, be attributed to radio packet loss.

Local processing and storage

The receiving station identifies the sensor associated with each message and applies the corresponding calibration through a table of input and output pairs, calculating intermediate values by linear interpolation between consecutive points. For flow rate, this conversion relates the calculated level to the flow defined by the operational reference, whereas turbidity is processed from the raw value

received from the node.

The application distinguishes the original reading from the converted value and retains a reference to the calibration applied, making it possible to review which reading entered the system and which adjustment was used before the result was displayed or recorded. This arrangement preserves the relationship between acquisition and processing, particularly when calibration points are modified.

During testing, the interface was updated after the received packets had been processed, while the persistence service had a configured interval of 15 minutes. These functions therefore operate on different schedules: the persistence interval describes the storage configuration and does not measure link latency or demonstrate that every packet is stored immediately after reception.

Testing procedure

Development checks included the construction, encryption, and recovery of synthetic messages using the system identifiers, along with a review of interpolation using known level and flow-rate inputs. The acceptance criteria were to recover the original identifier and value without changes and reproduce the expected interpolation outputs, keeping these software checks separate from observations of the physical link.

Before the temporary installation, a preliminary communication check was performed at an approximate separation of 50 m along a path that was not completely direct. Messages were observed arriving at the receiver, allowing communication to be checked functionally, although complete counts and records of signal strength, signal-to-noise ratio, and latency were not retained.

At the operational installation, the straight-line separation was estimated at approximately 35 m using a cartographic reference, with vegetation, structures, and differences in elevation between the nodes. Two mounting conditions were examined: the antenna inside the fully closed enclosure and its placement toward the cable opening, with the outlet sealed using silicone sealant. Figure 2 presents the equipment and installation evidence.

Figure 2. Components and temporary installation of the monitoring system



Note. From left to right, the figure shows the components of the transmitting node, the enclosure installed next to the measurement point, and the LoRa module connected to the receiving station. Source: Own work.

The functional acceptance criterion was to receive all three variables and complete the path defined by test case CP-SIS-001, from acquisition to access through the application. Reception was examined using a console excerpt, and the subsequent functions were reviewed through the corresponding integration cases. Complementary checks examined two points used to adjust turbidity conversion with the DR/890 colorimeter and a visual comparison of the estimated flow rate against a level and flow-rate scale.

Scope of the evaluation

The evaluation focused on the documented conditions of the prototype, as synchronized timestamps and a continuous record of defined duration were not available to calculate end-to-end latency or long-term availability. RSSI, the received signal strength indicator, and SNR, the signal-to-noise ratio, were not recorded either and therefore remained outside the quantitative results.

Personnel reviewed turbidity, flow rate, and the graphs during the session through exploratory, qualitative assessments based on their interpretation of the readings. This review did not include a structured survey or statistical measures of satisfaction or usability; the analysis is limited to technical records and operational assessments and contains no personal data.

RESULTS

Functional behavior of the link

The preliminary check showed communication between the nodes before they were moved to the operational environment and provided a basis for the temporary installation, although it does not establish a reception rate or allow a quantitative comparison of performance at different distances. Table 1 summarizes the conditions of both checks and the mounting changes observed during installation.

Table 1. Conditions and results of the LoRa link checks

Check	Approximate separation	Physical condition	Observed result
Preliminary	50 m	Path not completely direct	Functional message reception, without a complete count or signal record
Installation with internal antenna	35 m	Closed enclosure and obstructed path	No reception was observed
Installation with antenna outlet	35 m	Antenna directed toward the cable opening, with the outlet sealed using silicone sealant	Reception was restored; configuration accepted for the functional test

Note. The 35 m separation is a straight-line cartographic estimate. The checks did not include RSSI, SNR, or latency measurements, or a comparable procedure for calculating packet loss at different distances. Source: Own work.

Reception was restored after the antenna placement was changed. No messages had been observed at the receiver while the antenna was confined inside the closed enclosure, whereas routing it through the cable opening restored incoming data and allowed the functional test to continue. The opening was sealed using silicone sealant, and the resulting configuration was accepted for the test while maintaining protection around the outlet.

The difference shows that physical installation affected system operation, but the procedure did not isolate the effects of orientation, contacts, component proximity, or antenna confinement. The result is therefore associated with the change in mounting configuration, without attributing it to a particular radio-related cause that was not measured during the test.

Data reception and integration

Figure 3 shows the console excerpt used to review message identifiers and readability, in which complete sequences of the expected variables can be distinguished. Table 2 brings together the counts and complementary checks, separating reception records from the synthetic inputs used during development so that they are not interpreted as a single communication test.

Figure 3. Excerpt showing the reception of N1, N2, and N4 messages at the Raspberry Pi station

```
(venv) pi@raspberrypi:~/monitoring $ python3 -m src.main
[Persistencia] Modo Multi-Sensor activo. Intervalo: 15 min.
>>> [LoRa] Radio inicializado OK
>>> [LoRa] Thread iniciado
[AlertService] Servicio de alertas iniciado
>>> [LoRa] N1:601.6
>>> [LoRa] N2:0.0
>>> [LoRa] N4:33.1
>>> [LoRa] N1:601.6
>>> [LoRa] N2:0.0
>>> [LoRa] N4:33.1
>>> [LoRa] N1:601.6
>>> [LoRa] N2:0.0
>>> [LoRa] N4:33.1
>>> [LoRa] N1:601.4
>>> [LoRa] N2:0.0
>>> [LoRa] N4:33.1
>>> [LoRa] N1:601.5
>>> [LoRa] N2:0.0
>>> [LoRa] N4:33.1
>>> [LoRa] N1:601.4
>>> [LoRa] N2:0.0
>>> [LoRa] N4:33.1
```

Note. The identifiers correspond to distance, raw turbidity reading, and temperature, respectively. The excerpt shows received messages and is not a complete record of the session's transmissions. Source: Own work.

Table 2. Results of the reception and processing checks

Check	Source	Quantity examined	Documented result
N1, N2, and N4 sequences	Console excerpt	5 cycles	Five complete sequences, equivalent to 15 readable messages
Message construction, encryption, and recovery	Synthetic development inputs	300 messages	Identifier and value recovered without changes in all 300 cases
Level and flow-rate interpolation	Synthetic development inputs	5 inputs	Five results matching the expected outputs
Persistence, CP-BD-001	Documented integration case	test 1 execution	Reading stored and subsequently retrieved
Complete data path, CP-SIS-001	Documented system test case	1 execution	Complete acquisition-to-visualization data path

Note. The synthetic results correspond to software checks rather than field transmissions. Console messages do not allow an overall reception rate to be calculated without the corresponding transmitter count. Source: Own work.

The value received under N2 is a raw reading from the analog-to-digital converter, whose presence in the console verifies message identification but should not be interpreted directly as a measurement in NTU. Conversion takes place after reception and depends on the active calibration, so the console reading and the value displayed in the interface must be examined according to their respective processing stages.

Outside the selected excerpt, isolated omissions of a variable were observed without stopping the entire service, as independent transmission allowed the received messages to continue being processed. However, the absence of counters and sequence numbers prevents overall packet loss from being calculated or a distinction from being made in every case between a transmission omitted by the program and a packet that was sent but did not reach the receiver.

The integration cases documented the storage and subsequent retrieval of a reading, as well as the complete system data path, supporting the functional connection between reception, processing, persistence, and visualization in the executions examined. The console screenshot provides evidence of the visible messages, while the database and application checks support the subsequent stages.

Processing and adjustment of readings

The synthetic checks examined the recovery of encrypted content and interpolation calculations using known inputs, with results that describe software operation under the cases defined during development. Their interpretation is limited to those procedures, which do not include the physical conditions needed to estimate link range or measurement error in the installed sensors.

Figure 4 shows the interface and the reference used during one of the turbidity adjustments, whose values were entered into the calibration table and subsequently reproduced by the system.

Figure 4. Record of one of the points used during turbidity adjustment



Note. The interface shows the adjusted value, and the DR/890 displays the reference used during calibration. The numerical agreement corresponds to an adjustment point; the instrument reports FAU, while the application identifies the variable in NTU. In this screenshot, the interface retains the SEN0189 label, although the sensor used was the TS-300B. Source: Own work.

This agreement describes the adjustment of the conversion at the recorded points. Table 3 specifies the scope of the turbidity, flow-rate, and temperature checks, including the distinction between a calibration reference and an independent comparison.

Table 3. Scope of the complementary variable checks

Variable	Reference procedure	or Documented result	Scope
Turbidity	Two adjustment points using the DR/890	Numerical values 88 and 377 reproduced after adjustment	Adjustment-point of check; no independent validation or FAU/NTU equivalence
Estimated flow rate	Visual comparison with the level–flow scale	420 LPS displayed; observed level between the 400 and 500 LPS marks, nearer 400	Approximate operational agreement; error not quantified
Temperature	Acquisition, transmission, and visualization	Reading displayed by the system	Functional check without an independent reference

Note. Photographs of the instrument and interface are available for the turbidity point corresponding to 88. The point corresponding to 377 was documented during the same adjustment session and has an interface record. Source: Own work.

The DR/890 instrument reports turbidity in FAU, while the application identifies the variable in NTU, so numerical agreement between their displays does not establish metrological equivalence. According to the Centro Español de Metrología (n.d.), calibration must be distinguished from adjustment because it relates instrument indications to suitable measurement standards and their uncertainties. This check examined the reproduction of the points entered into the table; assessing accuracy would require a compatible procedure, traceable references, and observations different from those used to adjust the conversion.

After the calibrations were applied, the graphs showed segments without wide fluctuations during the visible intervals, a behavior described as short-term visual stability because no series of observations was collected under a defined procedure to estimate repeatability. The consistency of the output must also be considered alongside the water conditions and the processing applied, as it does not establish measurement precision on its own.

DISCUSSION

The systems developed by Silva Torres and Coello Hurtado (2020) and Jabbar et al. (2024) use gateways and connected platforms for water monitoring, while Pires and Gomes (2024) also include local

processing and Node-RED visualization. The present proposal shares local processing with the latter work, using a desktop application linked to MariaDB to bring together reception, conversion, storage, and data access. The analysis focuses on integrating these functions with the independent transmission of variables and on the mounting conditions observed during the temporary installation.

The comparison with Forhad et al. (2024) identifies a different implementation scope, as their architecture incorporates instrumentation, a programmable logic controller, and cloud services, compared with the ESP32 node and Raspberry Pi station examined here. These differences reflect design decisions for different needs; the available results do not establish economic superiority, equivalent measurement accuracy, or better performance relative to those systems.

The study documents the integration of multiparameter acquisition, independent messages, and local processing through a point-to-point LoRa link, including a mounting difficulty that directly affected reception during installation. Distinguishing message arrival from interface updates and persistence also clarifies the data path and avoids assigning the same operating interval to services that function differently.

Kabi et al. (2023) examined communication through RSSI and SNR records from different locations, also considering receiver height. Their procedure provides a reference for extending the evaluation of this prototype, whose documented tests focused on functional integration. Studying link performance would require simultaneous transmission and reception records, sequence identification, and measurements of signal conditions over defined periods, followed by repeated checks at other distances and with different configurations.

CONCLUSIONS

The developed architecture integrated multiparameter acquisition with reception and local processing through a point-to-point LoRa link, while the documented executions verified variable identification and the path followed by readings through storage and retrieval. These results correspond to the functional scope established for the prototype and the installation conditions examined.

The preliminary check and temporary installation provided observations at two approximate separations, without constituting a comparative evaluation of performance by distance. During the temporary installation, reception was restored after the antenna mounting was modified, showing that

the physical arrangement of components must be checked together with the software and connections, particularly when the enclosure and the path between nodes form part of the operating conditions.

Independent transmission of each variable allowed received messages to be processed when a sequence remained incomplete, although the absence of sequence numbers and acknowledgments prevented total packet loss from being reconstructed. Adding these records, together with RSSI, SNR, and latency measurements over defined periods, would allow a more detailed evaluation of the link and help distinguish transmission omissions from reception failures.

The calibration checks documented the conversion of readings and the reproduction of adjustment points, while the visual stability of the graphs and operational assessments complemented the functional review without establishing metrological accuracy. Applying the architecture in similar environments requires the link mounting and configuration to be examined and the calibration relationships to be defined according to the conditions of each installation.

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