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Desarrollo y pruebas de un sistema de red de sensores inalámbricos de bajo costo para la recopilación de datos ambientales

Development and testing of a low-cost wireless sensor network system for environmental data collection

Desenvolvimento e teste de um sistema de rede de sensores sem fio de baixo custo para coleta de dados ambientais

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Resumen

Este proyecto detalló el diseño e implementación de un sistema de telemetría inalámbrica de bajo costo para el monitoreo ambiental. El sistema se basó en nodos de sensores con placas Arduino y módulos transceptores de 2.4 GHz nRF24L01, utilizando el User Datagram Protocol (UDP) para una transmisión de datos rápida y eficiente. A través de una metodología iterativa, se desarrollaron dos prototipos: los nodos MK1 y MK2. Las evaluaciones iniciales revelaron fallos de diseño en la versión MK1, lo que condujo a un rediseño más robusto en el MK2, que incluyó una carcasa atornillada. Las pruebas finales demostraron un rango de comunicación de hasta 140 metros, lo que confirmó la viabilidad del sistema en entornos remotos. Las conclusiones del estudio evidenciaron que el proyecto cumplió con sus objetivos, sentando las bases para futuras aplicaciones escalables en monitoreo a gran escala.

Palabras clave: telemetría inalámbrica, Arduino, redes de sensores inalámbricos, monitoreo ambiental.

Abstract

This project detailed the design and implementation of a low-cost wireless telemetry system for environmental monitoring. The system was based on sensor nodes with Arduino boards and 2.4 GHz nRF24L01 transceiver modules, using the User Datagram Protocol (UDP) for fast and efficient data transmission. Through an iterative methodology, two prototypes were developed: the MK1 and MK2 ones. Initial tests revealed design flaws in the MK1 version, which led to a more robust redesign in the MK2 that included a bolted casing. Final tests showed a communication range of up to 140 meters, confirming the system’s viability for use in remote environments. The findings evidenced that the project met its objectives, laying the groundwork for future scalable applications in large-scale monitoring.

Keywords: wireless telemetry, Arduino, wireless sensor networks, environmental monitoring.

Resumo

Este projeto detalhou o projeto e a implementação de um sistema de telemetria sem fio de baixo custo para monitoramento ambiental. O sistema foi baseado em nós sensores com placas Arduino e módulos transceptores nRF24L01 de 2,4 GHz, utilizando o Protocolo de Datagrama do Usuário (UDP) para transmissão de dados rápida e eficiente. Através de uma metodologia iterativa, dois protótipos foram desenvolvidos: os nós MK1 e MK2. As avaliações iniciais revelaram falhas de projeto na versão MK1, levando a um redesenho mais robusto no MK2, que incluiu uma carcaça aparafusada. Os testes finais demonstraram um alcance de comunicação de até 140 metros, confirmando a viabilidade do sistema em ambientes remotos. As conclusões do estudo mostraram que o projeto atingiu seus objetivos, estabelecendo as bases para futuras aplicações escaláveis em monitoramento em larga escala.

Palavras-chave: telemetria sem fio, Arduino, redes de sensores sem fio, monitoramento ambiental.

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Introduction

Environmental monitoring is vital for disaster prevention, natural resource management, and the optimization of agricultural processes. This monitoring involves collecting data in remote, often difficult-to-access areas where traditional wired solutions are impractical due to their high cost and limited versatility. A viable and low-cost alternative is to develop a wireless telemetry system, which allows for the real-time acquisition of environmental variables such as temperature, humidity, and wind direction.

Currently, development boards like Arduino simplify the prototyping process for these systems (Lobo Varela, 2025; Romero, 2021). In conjunction with these boards, wireless sensor networks (WSNs) have become a relevant resource for real-time data collection, especially in large areas (Morán, 2015; Egea-López et al., 2004).

The literature on WSNs includes various examples of applications ranging from agriculture (Tobar Cuesta and Morán Solís, 2022) to urban environmental monitoring (Sánchez and García, 2018). Authors such as Santini et al. (2008) presented a comprehensive review of the communication protocols used in these networks; this review establishes that the UDP protocol offers advantages in telemetry applications due to its low data overhead. This proposal aims to establish a reliable and low-cost telemetry system, addressing the need for affordable solutions in the region.

The main purpose of this article is to present the design and implementation of a wireless telemetry system for monitoring environmental variables. The focus is on affordability, replicability, and scalability. The system is based on the creation of sensor nodes, which capture data, while a base station receives, processes, and stores it. This aims to demonstrate the viability of a solution that can overcome the limitations of traditional systems (López et al., 2021).

The article presents not only the implementation of a prototype, but also the development methodology that can be replicated and scaled up in future telemetry applications in large areas (Vivanco et al., 2024; Jaramillo, 2021).

The specific objectives of the project are:

- Design and prototyping: develop a functional prototype using low-cost development platforms such as Arduino.
- Component selection and validation: evaluate the nRF24L01 transceiver module and establish the UDP protocol to ensure efficient communication even in hard-to-reach environments.
- Performance testing: evaluate system performance through range and stability testing to achieve a communication distance suitable for field use.
- Creating a robust design: optimizing the system through continuous improvement cycles based on the results obtained with the initial MK1 prototype.

To achieve these objectives, the development of an infrastructure based on peripheral nodes capable of operating autonomously was proposed. The Arduino platform was chosen due to its versatility and the wide availability of libraries compatible with moderately accurate environmental sensors, making it ideal for projects where budget is a limiting factor.

The core of the wireless communication system was centered around the nRF24L01 module, which operates in the 2.4 GHz ISM band. This component was selected for its low power consumption and its ability to implement mesh networks, allowing data to "hop" between nodes until it reaches the base station. As Tomasi (2003) mentions, efficiency in digital data transmission is fundamental in electronic communication systems, especially when working with signals that must pass through physical obstacles.

In this context, it was determined that the system architecture should be modular. This allows the rest of the network to remain operational even if one sensor fails. The workflow was divided into hardware design (circuits and enclosures), firmware development for managing the UDP protocol, and finally, integration into a controlled test environment to measure real-world performance against the manufacturers' theoretical specifications. This pre-design phase laid the groundwork for building the MK1 and MK2 prototypes.

Method and material

Arduino UNO development boards, along with 2.4 GHz nRF24L01 transceiver modules, were used as the platform for creating the sensor nodes. The physical design included enclosures fabricated using 3D printing with polylactic acid (PLA) filament. Custom printed circuit boards (PCBs) were also designed and implemented to ensure the integrity of the connections. An Arduino UNO connected to a PC via USB was used for the base station for data management.

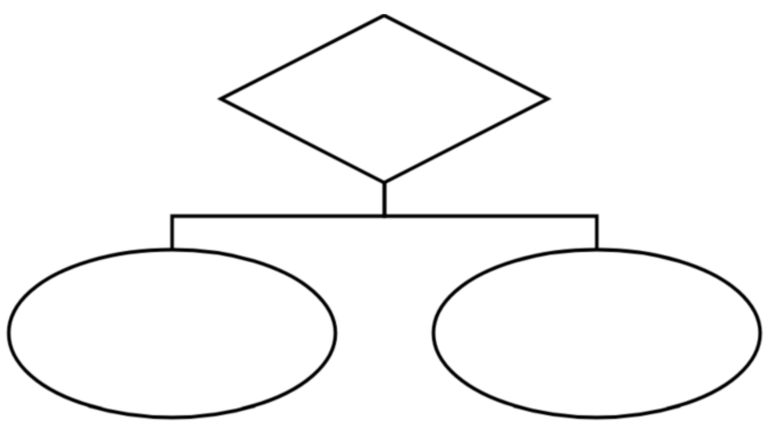
Procedure

The project was structured using an iterative methodology to ensure the robustness of the final prototype, minimizing technical risks and optimizing the system's scope. The process was divided into the following detailed phases:

Conceptual design and communication diagrams

In the initial phase, communication diagrams were designed to serve as architectural blueprints for defining the network topology. A basic configuration was established where a master node maintains a unidirectional connection with two first-level sensor nodes, as illustrated in Figure 1.

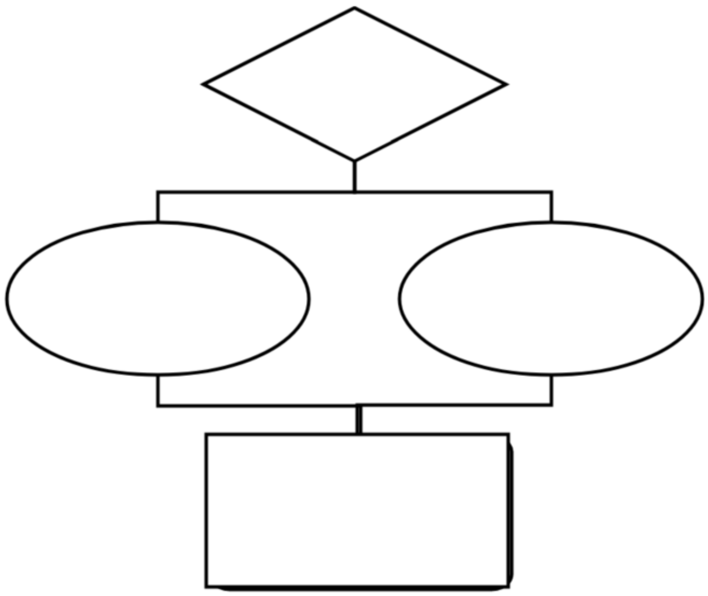
Figure 1. First communication diagram between master and first-level nodes.



Prepared from (Tomasi, 2003; Frenzel , 2001)

Subsequently, a mesh network architecture was developed that incorporated a third sensor node. In this scheme, the third node does not connect directly to the master node, but instead uses the first-level nodes as repeaters, allowing the system's geographic coverage to be extended; this configuration is detailed graphically in Figure 2. This scalability approach and development methodology is fundamental for telemetry applications in large areas (Vivanco et al., 2024; Jaramillo, 2021).

Figure 2. Second communication diagram between master nodes, first-level nodes, and second-level nodes



Prepared from (Tomasi, 2003; Frenzel , 2001)

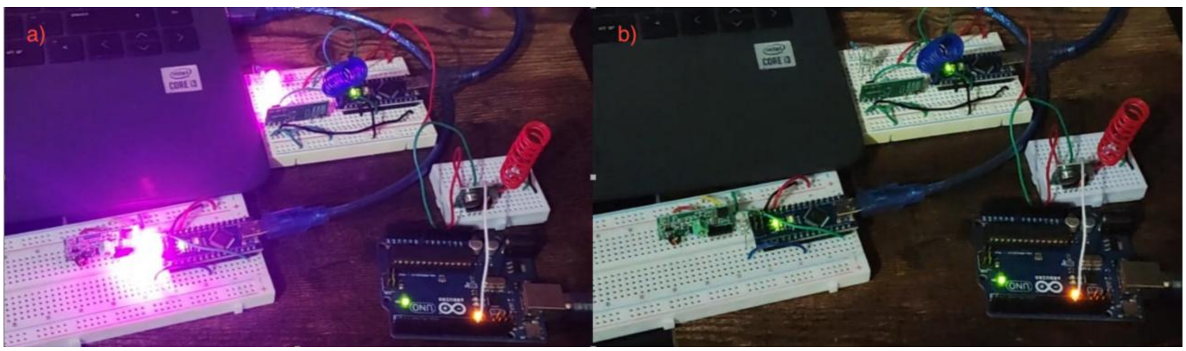
Protocol tests

After defining the topology, point-to-point communication tests were performed. The use of 315 MHz modules in broadcast mode was discarded due to the inability to uniquely identify the nodes and their high susceptibility to interference. Instead, the User Datagram The UDP protocol enabled organized and direct communication where the master node requests information from specific nodes. As Santini et al. (2008) indicate, the efficiency of the UDP protocol is key in low-power systems for structural and environmental monitoring. Initial functional tests confirmed the success of the transmission through remote control of LED indicators and verification of the data frame (Salgado Villanueva and Bacigalupo Chocano, 2025).

Data validation and physical design

The integrity of the information sent by the sensor nodes (temperature and humidity) to the base station's serial monitor was verified. It was confirmed that the received data matched the actual environmental parameters (Tobar Cuesta and Morán Solís, 2022). For the physical design of the components, the CAD software SolidWorks was used for the enclosures and the EasyEDA platform for the printed circuit board (PCB) design, the schematic of which is shown in Figure 3. Special attention was paid to protecting the internal components, integrating enclosures manufactured from PLA filament using 3D printing, seeking a structure that facilitated maintenance and protection from the elements (Sánchez and García, 2018).

Figure 3. First functional test: a) On b) Off.

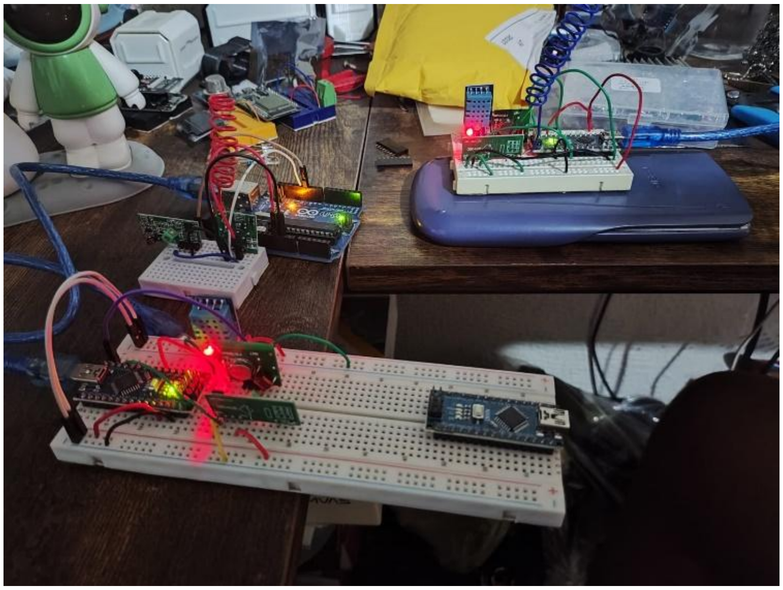


My own photographs

Validation and iterative redesign

During the validation phase, critical flaws were identified in the initial MK1 prototype. It was observed that the pressure-sealed housings caused weld breakage and internal connections to detach due to mechanical stress. In response, version MK2 was developed, incorporating a screw-lock system and external connectors for the nRF24L01 module antennas, as shown in detail in Figure 4. This redesign allowed the system to operate under the necessary technical robustness and stability conditions for field applications, minimizing data packet loss (Tomasi, 2003). Finally, stress and range tests were performed in open fields to determine the communication breakdown threshold, ensuring the system's reliability under real-world operating conditions (Trujillo Borja and Ávalos Gómez, 2023).

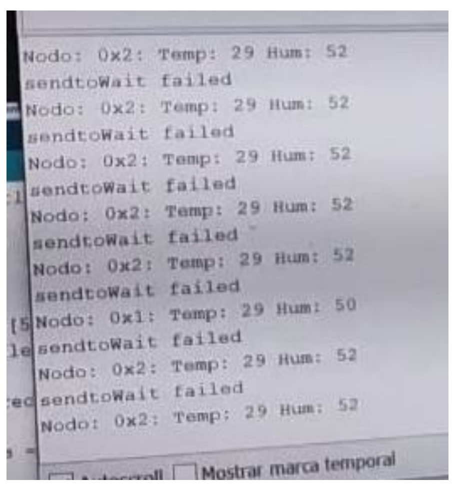
Figure 4. Second functional test "Datagram Server".



Own photograph

The results of the final implementation and deployment of the nodes in the test environment are shown in Figure 5, which confirms the stability of the mesh network under continuous operation.

Figure 5. Received data, displayed in the Arduino IDE serial monitor



Own photograph

Results

Following the implementation of the prototypes and the execution of field tests, significant data were obtained regarding the performance of the sensor network system. The results are presented in terms of architectural efficiency and the physical coverage achieved.

Network architecture performance. The viability of the mesh network architecture and the efficiency of the UDP protocol in maintaining organized communication between multiple nodes were confirmed. Validation of data reception at the base station confirmed that there was no critical packet loss during short- and medium-range tests. This behavior is consistent with the findings reported by Santini et al. (2008) regarding the reliability of lightweight protocols in monitoring environments. As shown in Figure 6, the monitoring interface allowed visualization of the arrival of temperature and humidity data frames sequentially and without overlap, validating the design of the developed firmware.

Figure 6. Completed MK2 nodes

Photograph by the author.

Hardware scope and robustness. The upgrade from the MK1 to the MK2 model drastically increased the mechanical robustness of the nodes, ensuring the protection of the electronic components. While the MK1 prototype exhibited failures due to material fatigue and cable detachment, the MK2 model maintained its operational integrity throughout the stress testing phase.

Regarding communication range, the implementation of optimized power supply circuits and the use of external antennas with a 2 dBi gain in the MK2 model's nRF24L01 modules resulted in a substantial increase in coverage. Open field tests demonstrated that the communication range increased from a mere 3 meters in the MK1 (due to interference and lack of a ground plane) to a maximum of 140 linear meters in the MK2.

Figure 7 presents a comparative graph of the range obtained, demonstrating signal stability at different distances and the communication breakdown point. These results exceed initial expectations for a low-cost system and align with the connectivity standards for precision agriculture discussed by Tobar Cuesta and Morán Solís (2022).

Figure 7. Terminated MK1 nodes

Own photograph

Discussion

The results obtained in this work validate the feasibility of using open-source, low-cost hardware platforms, such as Arduino, for the implementation of wireless sensor networks (WSNs) for environmental monitoring. This observation coincides with the findings of Lobo Varela (2025) and Romero (2021), who argue that the democratization of these technologies facilitates rapid prototyping in areas of scientific research.

Unlike the initial MK1 prototype, which suffered from structural flaws, the MK2 version demonstrated that physical robustness is just as critical as software efficiency in remote environments. Its achieved range of 140 meters surpasses the standard ranges of similar devices without optimized antennas, positioning this system as a competitive solution against more expensive commercial options.

Regarding the network architecture, the implementation of a mesh topology overcame the point-to-point range limitations, a concept aligned with the research of Egea-López et al. (2004) on WSN scalability. Furthermore, the choice of the UDP protocol proved crucial for minimizing latency and energy consumption, factors that Santi et al. (2008) identify as determining factors for the autonomy of sensor nodes in the field.

Finally, the integration of temperature and humidity sensors into a replicable design addresses the needs identified by Salgado Villanueva and Bacigalupo Chocano (2025) regarding the urgent need for accessible technological tools for modern agriculture and microclimate management. It can be stated that the discrepancy between investment cost and performance is minimal, fulfilling the premise of high efficiency at low cost.

Conclusions

Based on the results obtained, it is concluded that the design and implementation of the low-cost wireless sensor network system successfully met the stated objectives. The research demonstrated that it is possible to develop accessible and efficient technological solutions for environmental monitoring in remote areas using open-source hardware and lightweight communication protocols.

The transition from the MK1 to the MK2 prototype was determined to be a critical step in the development process. While the initial version validated the programming logic and the viability of the UDP protocol, the identified mechanical deficiencies underscored the importance of a robust physical design to ensure operational continuity. Implementing the MK2 model, equipped with external connectors and a bolted structure, resolved the integrity issues and allowed the nRF24L01 modules to reach their full transmission potential.

The achieved range of 140 meters in open field confirms that the system is suitable for telemetry applications in microclimates and medium-sized agricultural plots. Furthermore, the mesh network architecture validated in this study lays the foundation for future expansion, allowing the system to be scalable and replicable in environments with complex topography where traditional wired systems are impractical.

Finally, this project not only delivers a functional prototype but also proposes an iterative design methodology that can be adopted in other technological research projects. The successful integration of low-cost hardware with optimized software demonstrates that the technological gap in environmental monitoring can be significantly reduced through the strategic use of open-source tools and efficient protocols.

Contributions to future lines of research

The successful implementation of this low-cost system opens several avenues for future work. First, it proposes the integration of security protocols and data encryption to guarantee information integrity in larger-scale networks, as suggested by Trujillo Borja and Ávalos Gómez (2023). Furthermore, it envisions a migration to long-range technologies such as LoRa , following the autonomous systems methodologies proposed by Vivanco et al. (2024), which would allow coverage to be expanded over kilometers without significantly increasing energy consumption.

Another identified line of research involves implementing artificial intelligence algorithms at the base station to predict climate trends based on historical data collected by sensor nodes. As Salgado Villanueva and Bacigalupo Chocano (2025) point out, the transition to Agriculture 4.0 requires not only data capture but also its intelligent processing for real-time decision-making. Finally, the development of a dedicated mobile interface is recommended to facilitate data visualization for end users in the field, optimizing the user experience reported in previous studies (Jaramillo, 2021).

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