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Design proposal of a wireless sensor and actuator network for irrigation, based on Internet of Things technology

Propuesta de diseño de una red inalámbrica de sensores y actuadores para riego, con tecnología de Internet de las Cosas

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Abstract

Objective: This paper presents a detailed selection of IoT technologies for the design of an ambient humidity monitoring infrastructure to control crop irrigation. **Methodology:** The prototype design was supported by previous studies carried out by the authors and tests in 2019 at Finca el Porvenir in Cundinamarca, Colombia, in order to determine the best option to implement in the field through the use of Python software, and elements such as Raspberry Pi and the TTGO development board. **Results:** To determine the functionality of the software and hardware of the system, different static tests of the prototype were carried out by monitoring humidity and ambient temperature by means of the DHT22 sensor, whose information is sent from a transmitter node to a receiver node in a concentrator to later save the information in a database and, finally, to obtain graphs of the behavior of the relative humidity, temperature, and the actuation of the control element (solenoid valve). **Conclusions:** With this information it is possible to demonstrate the effectiveness of the prototype, the possibility of remote connection with the LoRa protocol and the handling and management of information from different crop areas through the GUI on the Raspberry Pi, generating a low-cost solution for access by small and medium producers in rural areas in Colombia.

Keywords: automatic irrigation, LoRa protocol, rural application, wireless communication, WSAN.

Resumen

Objetivo: Este trabajo presenta una selección detallada de tecnologías IoT para el diseño de una infraestructura de monitoreo de humedad ambiental para el control del riego de cultivos. **Metodología:** El diseño del prototipo se apoyó en estudios previos realizados por los autores y en pruebas realizadas en 2019 en la Finca el Porvenir en Cundinamarca, Colombia, con el fin de determinar la mejor opción para implementar en campo mediante el uso del software Python, y elementos como la Raspberry Pi y la placa de desarrollo TTGO. **Resultados:** Para determinar la funcionalidad del software y el hardware del sistema, se realizaron diferentes pruebas estáticas del prototipo a través del monitoreo de humedad y temperatura ambiente por medio del sensor DHT22, cuya información es enviada desde un nodo transmisor a un nodo receptor en un concentrador para, posteriormente, guardar la información en una base de datos y, finalmente, obtener las gráficas del comportamiento de la humedad relativa, la temperatura, y el accionamiento del elemento de control (válvula solenoide). **Conclusiones:** Con esta información es posible demostrar la efectividad del prototipo, la posibilidad de conexión remota con el protocolo LoRa y el manejo y gestión de la información de diferentes zonas de cultivo a través de la GUI en la Raspberry Pi, generando una solución de bajo costo para el acceso de pequeños y medianos productores en zonas rurales de Colombia.

Palabrasclave: aplicación rural, comunicaciones inalámbricas, protocolo LoRa, riego automático, WSAN.

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Introduction

Climate change is one of the major concerns highlighted in the Sustainable Development Goals (SDGs). By 2019, the hottest decade on record came to an end, and although, due to the restrictions caused by the pandemic, CO2 emissions are expected to decrease by 2020, this does not imply that accelerated climate change has slowed down or that it is over [1]. In recent years, climate change has been responsible for reducing many natural resources, including water, since its effects include lack of water, decrease in its quality, changes in its salinity and increased irrigation in certain sectors and applications due to soil drought. All of the above has negative implications for biodiversity and affects the costs of implementing strategies to fight the emergency [2].

In addition, the 2020 report of the Food and Agriculture Organization of the United Nations (FAO) makes a special request to consider the relevance of water and the limitations that currently exist in relation to this resource. It states that approximately one sixth of the population lives in areas with water stress, which generates a threat to the ecosystem and, of course, to the economic growth of these areas [3]. In this sense, improving the management of water resources is essential to enhance crop yields and thus mitigate climate change, at least in terms of these resources. However, implementation of these strategies by farmers does not depend only on their own will but must also consider aspects such as water accessibility, water risk, uncertainty due to the changing climate, costs of other necessary inputs, and actual benefits that can be obtained from water management strategies [3].

These are not the only problems; it is also clear that interest in agriculture and its development has decreased in some developing countries, as in the case of Latin America, where in countries such as Colombia, the future possibilities of farming are not clear, and the population is migrating to the big cities. This migration is not unique to this continent; it can be seen in other countries, as in the case of India, where it is becoming a more materialized reality every day [4]. Therefore, the Ministry of Science and Technology of Colombia (MinCiencias) has mentioned in the 2017 working document on the SDGs and the contribution of science, technology, and innovation (STI), that a successful contribution to the SDGs is not a simple effort of academia and its research groups, but that efforts must be in conjunction with several factors such as civil society, industry and, of course, the government [5]. Thus, developments aimed at mitigating negative effects on climate -and its resources- should be encouraged from different agencies and should be implemented in collaboration with different actors as mentioned above.

Because of the above, it has been stimulated research on new strategies to mitigate climate change and, in addition, to develop new projects that are useful in developing countries to improve processes where water resources are important and cannot be left unused.

Therefore, an important concept today is Digital Agriculture (eAgriculture), consisting mainly of initiatives that use Information and Communication Technologies (ICT) [6], as well as Internet of Things (IoT) with hardware and software platforms [7]. Likewise, wireless sensor and actuator networks (WSAN) have permeated the concept of IoT application in agriculture, due to the ability of these platforms to be sustainable over time and consume few energy resources for their operation. These networks are characterized mostly because they use small-sized devices, make use of wireless networks, the reception and transmission nodes are spatially distributed and powered by batteries, they use radio protocols in ISM free band, environmental data is obtained by sensors and, together with the final control elements, they are connected from a microcontroller [8]. Usually, these platforms tend to have a low associated cost, hence their importance and relevance for application in agricultural environments and in very specific tasks in this context [7].

This paper will present a design proposal for irrigation management for an agricultural crop using IoT and WSAN concept. First, a search for similar works in a global context was carried out, in order to evaluate the different platforms and alternatives for IoT technologies application; second, the platform and architecture suitable for handling an irrigation task was defined, using 1 actuator for each field node together with an ambient humidity sensor, and an information concentrator with a data server, which together with a user interface, allows the administration and management of crop irrigation. Finally, tests of the sensor used, and the actuator were performed to verify its operation with the proposed infrastructure and software, through some static tests in a greenhouse, leading to the discussion of the results to end with the reflections of the article.

A: Previous Work

In order to develop this work, over the previous two years a process of research and technology application has been carried out as part of the project entitled "Application of an IoT development with precision agriculture techniques for a flower crop" (Aplicación de un desarrollo IoT con técnicas de agricultura de precisión para un cultivo de flores), focused on establishing the advantages and disadvantages of the implementation of technologies associated with IoT in a rural context, and more specifically, in a flower crop.

Thus, in 2019, a comprehensive review of the state of the art was consolidated in order to state methods, architectures, software, and hardware technologies applied in IoT in the agricultural context. From this search, the paper entitled "Internet of things applied to agriculture: current status" (Internet de las cosas aplicado a la agricultura: estado actual) [7] stands out, where a compilation of different published documents regarding IoT projects applied to agriculture in the world, with special emphasis on Latin America, was compiled. It also showed the current status of the software and hardware tools most widely used in IoT architectures in the agricultural context.

From previous review study, it began with an identification of the best platform for a WSAN application for irrigation control, in order to optimize agricultural processes and water performance. However, one of the main difficulties for its application is the use of wireless networks under Colombian context, largely due to the lack of infrastructure, natural flaws provided by the rural environment, and of course, the great digital gap in the country. As a result, the best technologies were identified (as evidenced in the methodology) and whose choice was largely due to field test implementation of a communication protocol (LoRa), and some hardware technologies studied in the first document [7]. Therefore, in October 2019, an evaluation of LoRa technology as a communication protocol was carried out within the area where the flower crop associated with the research project is located. The protocol evaluation study can be evidenced through the paper " Performance evaluation of LoRa technology for implementation in rural areas" [17].

Materials and methods

A: Methodology

In order to accomplish the proposed design, an applied research was used, which starts from a social need as well as productive field, where it is sought to conceive an idea that materializes and takes into account the perceptions of the end user (in this case small or medium rural producers) in order to find an acceptance in the agricultural field, allowing to provide real design usability in a real prototype and its subsequent technology transfer [18]. In addition, based on the aforementioned previous research, a question to be answered in this design is proposed as follows: What kind of IoT architecture can provide a better performance of an irrigation system in a crop to optimize the process and thus contribute to climate change mitigation and the difficulties that water resources have in this new century?

The methodology is divided into four phases:

1. State of the art of IoT technologies in irrigation systems.
2. Selection of software and hardware materials for IoT infrastructure in irrigation systems.
3. Realization of the network infrastructure and firmware for irrigation management.
4. Experimental tests in a greenhouse crop.

B: State of the art

Starting from the investigation question, a state-of-the-art search was carried out in order to identify documents within the last 7 years that included any of the following topics: WSAN, irrigation control and management, IoT in agriculture, alternative communication protocols (LoRa, ZigBee, SigFox), multipoint communication and open-source software and hardware. From this systematization, the documents shown in Table 1 were selected. Subsequently, hardware and software elements necessary for the implementation were selected and tested. Likewise, wireless communication infrastructure framework for the system was determined.

Table 1. Works identified for IoT irrigation systems in different parts of the world.

Title	Year and country of contribution
Gsm Based Low-Cost Smart Irrigation System with Wireless Valve Control [9].	2017, India
Wireless sensor network with irrigation valve control [10].	2013, USA
Design and Implementation of a LoRa Based Wireless Control for Drip Irrigation Systems [11].	2017, Italy
Agriculture monitoring and smart irrigation system based on wireless sensors [19].	2019, India
An automated irrigation system for smart agriculture using the Internet of Things [12].	2018, India
IoT based wireless sensor network for precision agriculture [13].	2019, Pakistan
FARMNET: Agriculture support system using wireless sensor and actuator network [20].	2017, India
Agrinex: A low-cost wireless mesh-based smart irrigation system [16].	2020, Philippines
Design of a smart water-saving irrigation system for agriculture based on a wireless sensor network for better crop yield [21].	2018, India
Automatic drip irrigation system by deploying IoT on agriculture [22].	2020, India
Design of intelligent farmland environment monitoring system based on wireless sensor network [14].	2020, China
Design and implementation of intelligent controller of low voltage solenoid valve based on ZigBee [23].	2018, China
IoT based power efficient agro field monitoring and irrigation control system: an empirical implementation in precision agriculture [15].	2018, Bangladesh
Review on IoT based precision irrigation system in agriculture [4].	2020, India
An ISM-Band automated irrigation system for agriculture IoT [24].	2020, USA
Precision water irrigation system for agriculture using IoT framework [25].	2021, India
Irrigation remote control system based on LoRa intelligence [26].	2020, China

Source: Own elaboration

In this sense, a series of projects found in different parts of the world are presented below, in order to provide an overview of the scope of this project for determining what is the additional contribution made by this design in irrigation systems.

The first paper dates back to 2017 [9], where a smart irrigation system was developed using a PIC 16F877A microcontroller, a SIM900 GSM module, an RF transmitter and receiver in ISM free band, that used a BF494 transistor and a LM558 comparator circuit, a HT640 encoder, a HT648 decoder and a voltage source with a 7805-regulator connected to a 12 Volt regulator. The sensor data in the field is sent to the microcontroller in a decoded form and is displayed on a mobile phone once the GSM message has been sent. Moreover, based on the sensor reference values, an activation or non-activation signal is sent to the valve controller circuit via RF communication.

In another paper from 2013 [10], a wireless network was developed, consisting of battery-powered and solar recharged nodes (radio transceivers) that were communicating with other nodes and a base station. The base station (Gateway) was a standard 32-bit computer running Linux (Ubuntu) connected by USB to a base radio. The computer was connected to Internet through a wired or wireless local area network (LAN). The system used a mesh network topology, meaning that nodes could relay messages to each other, thus providing multiple communication paths between each node and the base. Communication in this system used a 2.4 GHz radio frequency. Field testing included two different tests: a maximum distance of 1610 meters in direct line of sight, and 175 meters with obstacles. A total of 54 valves were used and communication and stress tests were conducted for one consecutive year.

Another work that provides evidence of a wireless irrigation system implementation is the one proposed by [11]. In this project, the authors develop a wireless communication based on LoRa communication protocol. Node boards were designed containing the following components: SX1278 LoRa module to work in 433 MHz frequency, an Atmega328P microcontroller, 4 batteries in series to provide 6v power supply, a 3.3 V voltage regulator, a 24 V DC-DC converter TPS61175, and a DRV8801 bridge controller circuit. Regarding the master board, it was used same design of the nodes, but an ESP-01 Wi-Fi module was added. It was determined the functionality of each board from the firmware used in each microcontroller. User communication interface was done through an application in Python language and was tested in Linux and Windows distributions. The application allowed the user to review actual valve status, and to control activation time to initiate irrigation. Additionally, it had the ability to edit, remove or add control valves.

A paper submitted in 2018 by [12] proposes an automated irrigation system. The proposed system consists of an internet of things architecture to minimize water consumption in agriculture. The elements used include: WEMOS D1 controller with an ESP8266 microcontroller including a WiFi module, solenoid valves operating at 24 V, YL69 soil moisture sensor and YF-201 flow sensor. For data transmission purposes the system used GPRS over mobile networks, sending controller status messages over the Internet. Detailed data could be provided through a ThingSpeak server via a web application, including some data such as pH, temperature, and soil moisture. Finally, the authors adjusted the irrigation control by means of a numerical model in Matlab software, in order to get the best irrigation method in the field, based on sensor data.

Another paper was postulated in 2019 by [13]. In this project the authors propose a system that used Arduino Uno as microcontroller, connecting soil moisture, environmental humidity, environmental temperature, ultraviolet incidence, and air quality sensors. Collected data was sent through a wireless connection using an XBEE module using the IEEE 802.15.4 communication standard. To centralize all data, the server was designed with an ESP8266 microcontroller, which sends it to a cloud server for further analysis in a MATLAB GUI on a PC. The server in turn, acts as the controller for the irrigation system, as these elements do not use wireless communication for this task. Each sensor node is powered by a 12 V battery that can be charged by a solar panel.

Another work implementing a more recent wireless communication protocol is found in [14]. The proposed design consists of a hardware and a software system. Hardware system consists of temperature and humidity sensor, NPK sensor, Arduino MEGA development board, electric valve, IoT-NB module, power module, hub, and a PC. The software system, on the other hand, consists of a LabVIEW environment in which it can be seen through an intuitive oscillogram that shows all sensor values and all data collected from irrigation, which are stored in a database.

Precision agriculture is a concept that allows consolidating efficiency and real-time crop management, but it is designed for large extensions and large-scale farmers. The following work [15] contributes with a proposal for an irrigation control system that is not necessarily for such a context. The proposed platform consisted of an architecture based on LoRa communication, with end nodes for reception and transmission, a gateway, and an API service through a mobile and web application. In total there are 3 types of nodes: sensor node, hub node, irrigation node; likewise, there is a database, a web application, and an Android application. The sensor node consists of an Arduino nano, a SX1278 LoRa transceiver, sensors for measuring ambient temperature and humidity, soil moisture and soil temperature. The whole node is powered by a 6 V battery. Meanwhile, the hub node consisted of an ESP8266 microcontroller, a SX1278 LoRa transceiver module and a 6v battery. This hub node is communicated by WiFi to the Internet with its integrated module, providing a direct communication to the servers and the developed APIs.

In both applications, identical field sensor data can be observed. Finally, the irrigation node was proposed using same considerations as the sensor node, except for the sensors, and adding two very particular features: a solenoid valve controller circuit and a panel with its respective circuit for solar charging with battery. Irrigation control is achieved either by programming valve activation times (from the application), as well as manual opening or closing from the APIs.

For the other hand, [16] presents a low-cost network application of the mesh network concept. The Agrinex application is a wireless sensor and actuator network that provides several capabilities: multiple sensors, drip irrigation as an actuator and a dynamic mesh network. The web application provides users these features: data visualization, node status and task scheduling. For measurement node implementation, the authors made use of an Atmega328 microcontroller, an nRF24L01 RF communication module, a DFRobot soil moisture sensor, a DHT11 humidity and ambient temperature sensor.

Additionally, this node also has an actuator by using a servomotor and a step valve, controlled from the microcontroller. A data reception node was implemented with a Raspberry Pi, where an nRF24L01 module was connected to collect all data sent from the measurement nodes. A web application using a local database allows viewing obtained data, these data are sent in a time frame of 3 minutes when working from the measurement node to the receiving node and 15 minutes when sending in the opposite direction.

C: Selection of software and hardware materials

Once the information on the state of the art was obtained, a comparison was made between several applications that were presented, identifying those technologies that were used in such projects. A consolidated information was then compared with previous reviews of the present project, and thus, the trends of use in software, hardware, and communication tools for the layers of the IoT infrastructure were established. The information is given in Table 2.

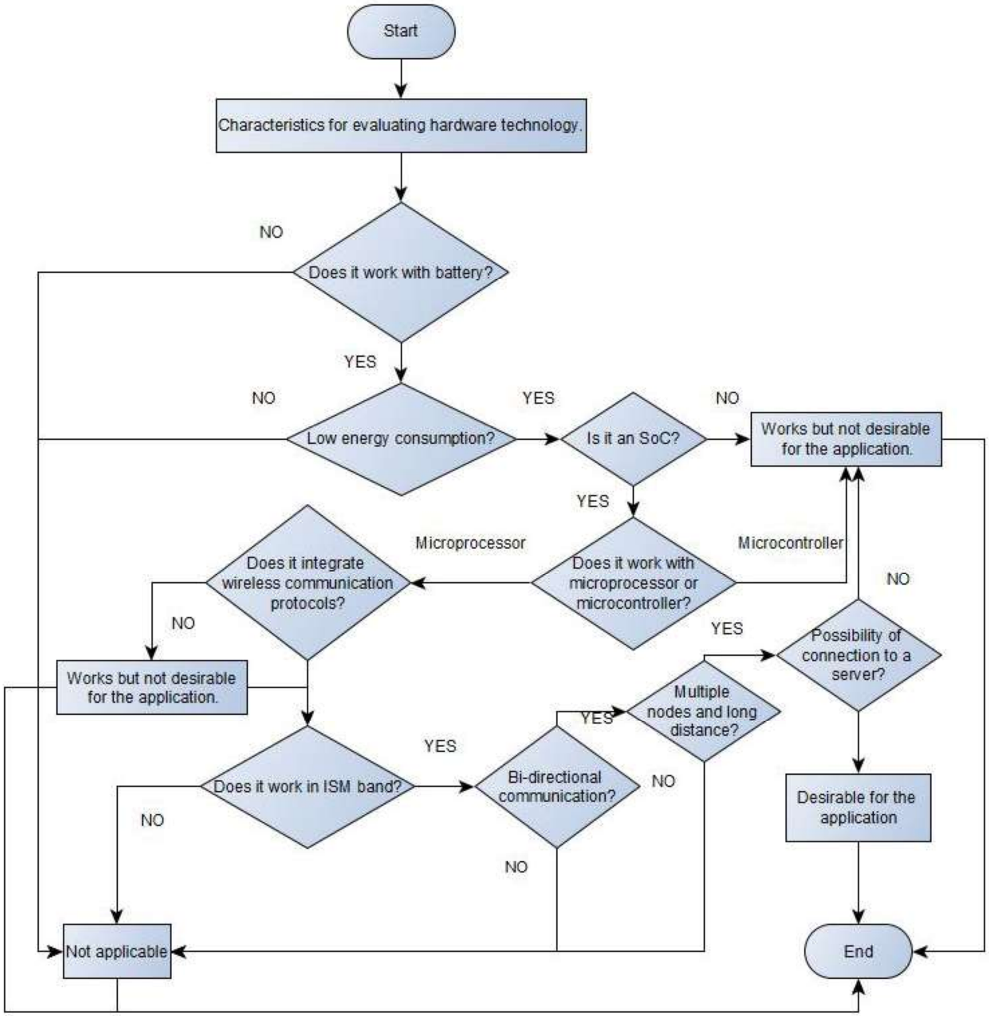
Table 2. Hardware, software, and communication technologies identified for the layers of the IoT infrastructure on irrigation systems.

Layer	Technologies
Perception	Microcontroller: PIC, Atmega, ESP8266, MSP430. Single Board Computer: Raspberry Pi. Controller: PLC. Actuators: Solenoid Valve, relay, irrigation pump, bridge H, motor. Sensors: DHT11, YL69
Application	Firmware for microcontroller: Procesing (Arduino), C. GUI: Python, PHP, HTML, JavaScript, Matlab, android.
Network	Transceiver modules: GSM SIM900, ADM3485ARZ, WiFi ESP-01, nRF24L01, ZigBee ZM2410, SX1278 LoRa. Communication technologie: LoRa, ZigBee, GSM, GPRS, WiFi. Servers: ThingSpeak, LocalHost.

Source: Own elaboration

Then, a selection algorithm was used to exclude those devices that do not provide the best performance for an IoT architecture. This algorithm can be seen in Figure 1. In this algorithm, the selection of low power devices using battery refers to those that allow a hardware autonomy in periods of time longer than one day, and thus, current levels lower than 250 mA with a voltage consumption between 3.5 V and 5 V. On the other hand, when mentioning the feature of multiple nodes and long distances the search refers to those devices in which networks of objects can be achieved over 10 nodes and distances greater than 500 meters.

Figure 1. Decision algorithm for hardware and communication technology selection.



Source: Own elaboration

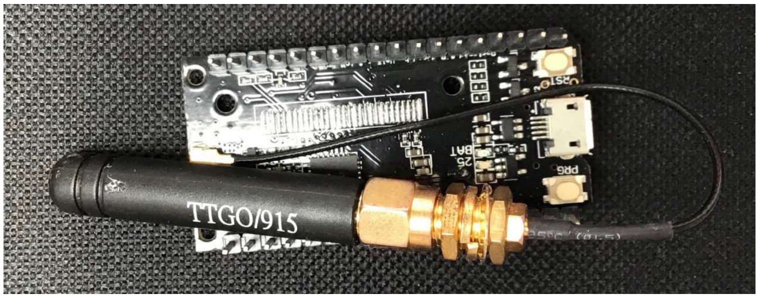
Given the previous information, it was found that the best option in hardware and communication technology for receiver and transmitter nodes, both for its characteristics and its use in previous work [17], is the LilyGO development board with part number TTGO LoRa32 V1.0.0 (28) (see Figure 2), whose characteristics are shown in Table 3.

Table 3. Features of product reference TTGO LoRa32 V1.0.

Characteristic	Description
Microprocessor	Tensilica LX6 dual Core -Espressif ESP32.
Transceiver	WiFi 802.11 b/g/NHT40. BLE. SX1276 Semtech.
Serial Protocol	CP2102
Antenna	2dBi
Communication Protocol	WiFi, Bluetooth, LoRa.
Voltage	3.3 V-7 V
Temperature range	-40°C to 90°C
Sensibility of receiver	-98dBm
Transmission power	19.5dBm, 16.5dBm, 15.5dBm
LoRa function	Power: 20dBm. Frequency operation: 868/915 MHz. Sensibility: -148dBm.

Source: Own elaboration

Figure 2. TTGO LoRa32 V1.0 development board.

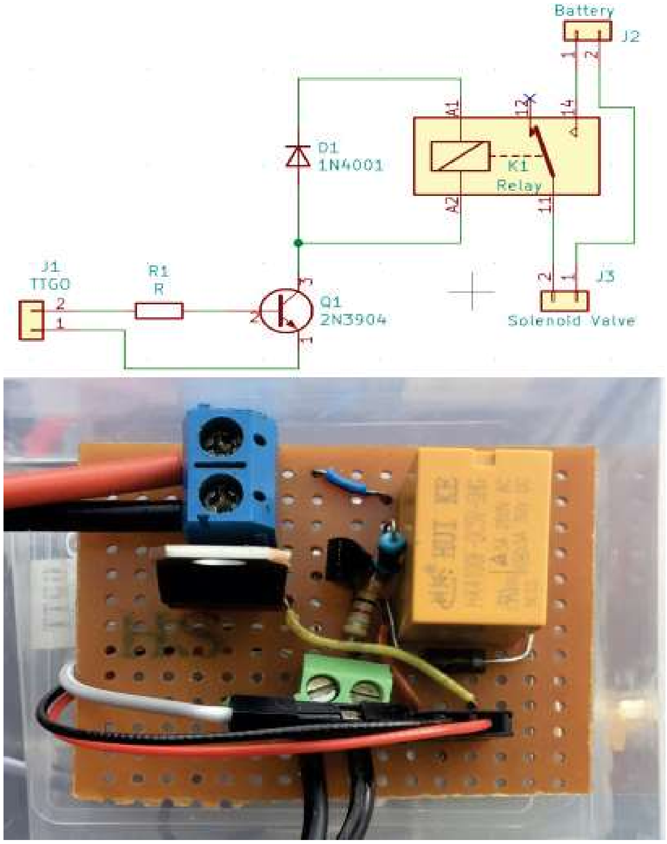


Source: Own elaboration

On the other hand, in order to be able to perform an irrigation action in the receiving node, a circuit composed by a solenoid valve whose state variation is performed by means of an electromagnetic relay was determined as the final control element. The relay is controlled by a digital signal from the TTGO (see Figure 3). This circuit in turn works as a coupling between digital electronics section and power section, avoiding any damage due to discharges or overvoltage on the board.

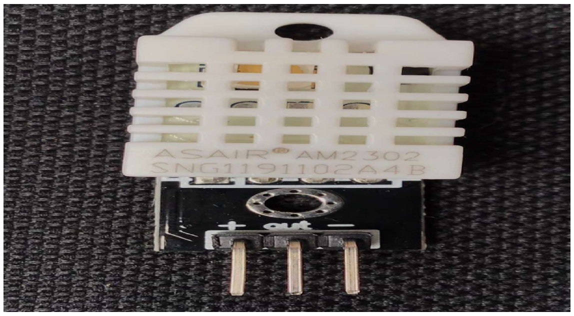
Regarding sensors, DHT22 (see Figure 4) was chosen due to its greater measurement range than its successor DHT11, and its regular use in the projects reviewed in the state of the art. It is communicated via single-wire transmission and can be connected to any GPIO terminal of the SoC used. In addition, the DHT22 sensor has a low supply voltage (3 to 6 V), a temperature measurement range between -40°C and 80°C, useful for the controlled environment of the test greenhouse, a temperature measurement accuracy of less than 0.5°C, a relative humidity measurement range between 0% and 100% with a relative humidity accuracy of 2%. Sampling of the magnitudes can be carried out with a minimum time of 2 seconds and upwards, a characteristic that is in accordance with obtaining measurements in the field for this type of agricultural processes that do not require such short times to obtain data.

Figure 3. Final control element circuit and power coupling. Electrical diagram and board implementation.



Source: Own elaboration

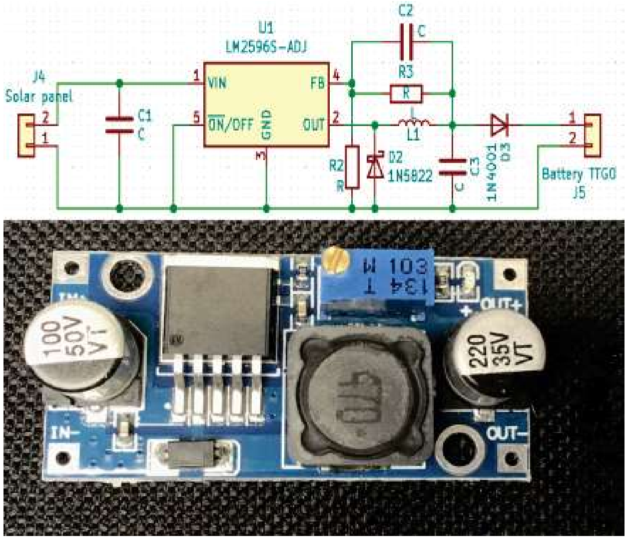
Figure 4. Relative humidity sensor with integrated temperature sensor DHT22.



Source: Own elaboration

The transceiver node, which is located in field, is powered by a 6 V VRLA (Valve Regulated Lead Acid) battery that is subsequently regulated to 5 V, in order to provide continuous power to the TTGO board, while receiving data from the hub. Since the system requires autonomy, it was decided to add a charging system from a solar cell with a maximum output of 9 V in use cycle, and a maximum of 7 W of delivery for charging. Connection drawing of the battery charging system for this node is shown in Figure 5.

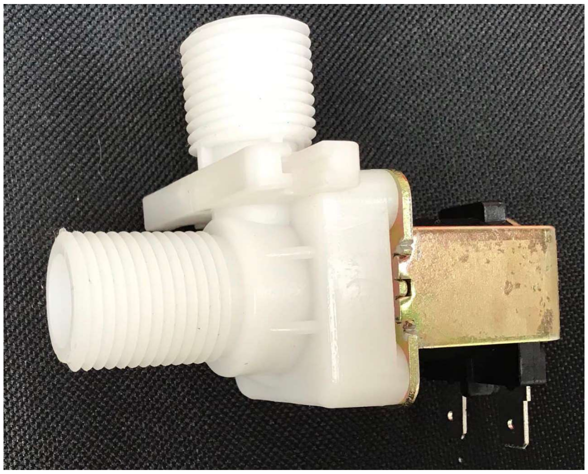
Figure 5. Power supply circuit for receiver node. Electrical diagram and assembled board.



Source: Own elaboration

In addition, the final control element must be powered by a 12 V battery to drive the solenoid valve (see Figure 6). This design leaves the chance of connecting a solar cell for valve autonomy, in order to avoid power outages in control system. The solar charging scheme that could be implemented is identical to that shown in Figure 5.

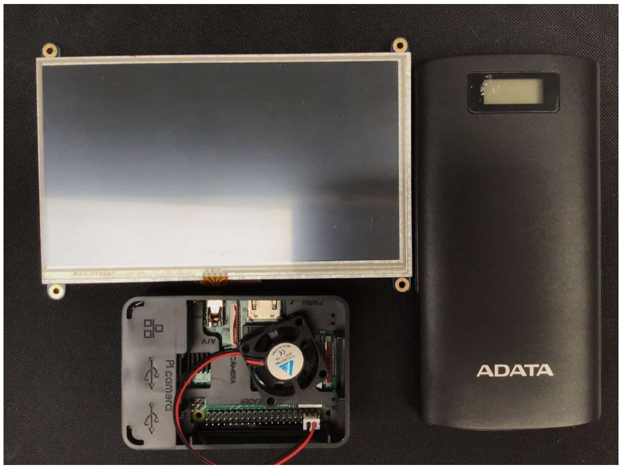
Figure 6. Solenoid valve as final control element.



Source: Own elaboration

Finally, a single board computer (SBC) Raspberry Pi was used as a data hub and base station, where a TTGO development board was connected as a transceiver node. The Raspberry Pi allows GUI programming from different freely usable programming languages such as Python, Java, C and PHP, and provides a Linux-based user environment. In addition, the base station uses a 7" touch screen to display information, as well as external peripherals to input information into the user interface. Raspberry Pi is powered through a 20000 mAh capacity power bank, providing approximately 48 hours continuous operation (or slightly more) over time. The aforementioned elements are shown in Figure 7.

Figure 7. Power bank, Raspberry Pi and Touch Screen used as base station.



Source: Own elaboration

D: Wireless network infrastructure

By selecting the TTGO development board, which includes the option of wireless communication with LoRa, the type of network infrastructure to be used was determined and data transmission parameters for this protocol were established.

First, parameters associated with transmission were determined based on the previous work observed in [17], identifying the best yield for El Porvenir farm, and whose characteristics are in line with many of the applications for rural areas in Colombia. Therefore, Table 4 details each parameter to be used.

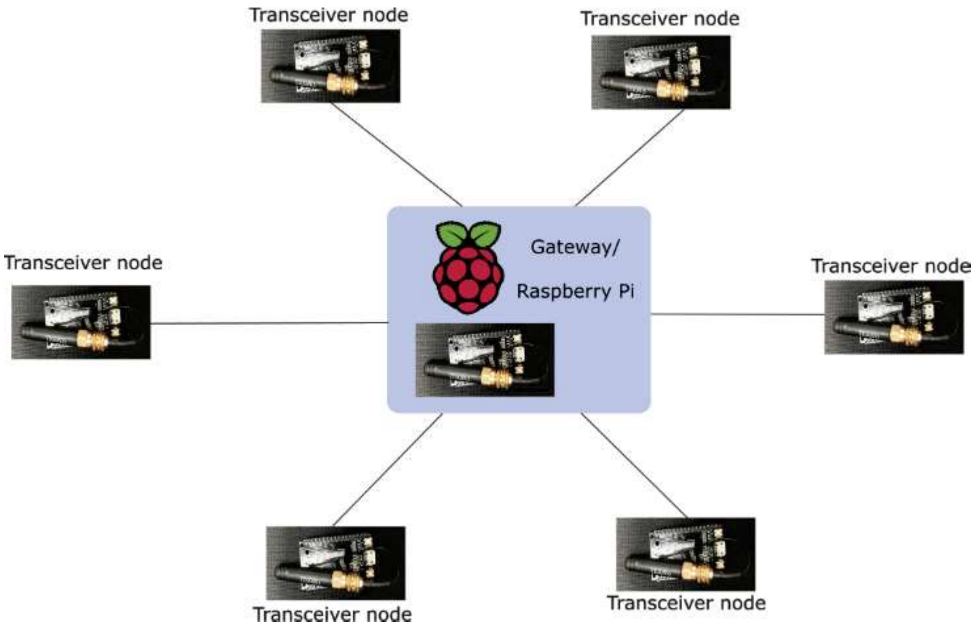
Table 4. Parameters to be used in LoRa protocol.

Parameter	Value
Spreading Factor	9
Bandwidth	125 kHz
Coding Rate	4
Header	Explicit Mode
Frequency of the radio	915 MHz

Source: Own elaboration

Next, wireless network connection type was established. Since the SX1276 module only works on one transmission channel in order to use the LoRa protocol, it was decided to adopt a star type, where there is a central node (hub), and all the operations, both sending and receiving data (according to the process operation), pass through it. Therefore, the structure for the present design is shown in Figure 8, where there is a hub and 6 field nodes.

Figure 8. Network architecture in star topology for the irrigation control system.



Source: Own elaboration

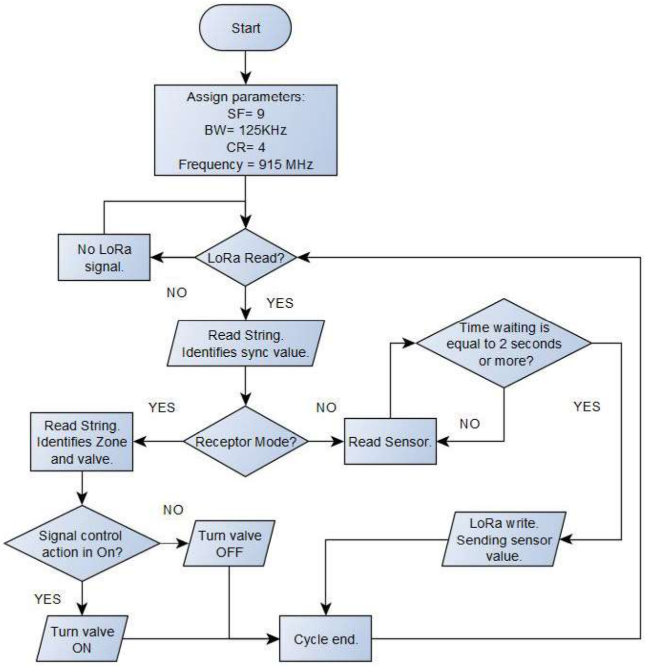
E: Firmware and programming

Due to the use of a SoC (system on chip) as a transceiver element, it is required to use firmware for its management and control. Currently, most manufacturers have released and provided libraries for programming development boards in the well-known IDE (Integrated Development Environment) Arduino, so this development environment was used for this project.

In order to achieve the best modularity of its associated software, two firmware programs were implemented, one for the hub, and another for the field node. Both programs used the library provided by Sandeep Mistry, as well as independent functions for each associated task of synchronization of receiving or sending data through LoRa protocol, so that reading the code and correcting possible errors would be easier.

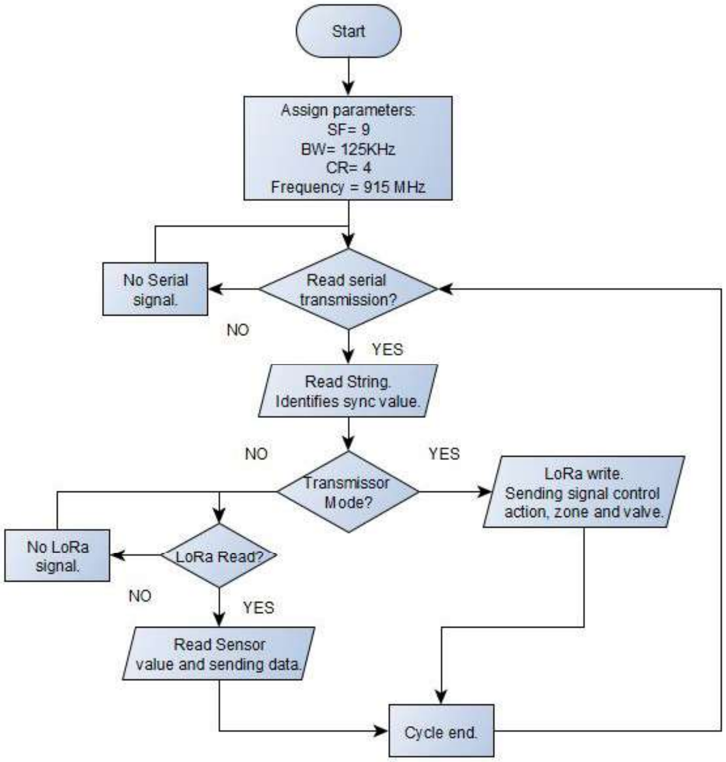
In addition, to avoid saturating the communication channel, and given that only a single data transmission channel can be used (and all possible nodes of the infrastructure can receive or transmit), it has been determined that sensor readings at the field nodes will only be activated at certain times of the day. This prevents the nodes from taking wrong data from the environment, which will be distinguished by synchronization values, and will be identified by the firmware in order to read only required data. This is achieved through synchronization words sent in each character string. Figure 9 shows the flow diagram of the field transceiver node firmware. Figure 10 presents the firmware associated with the hub transceiver node.

Figure 9. Firmware for field transceiver node, for valve control action and humidity sensor reading.



Source: Own elaboration

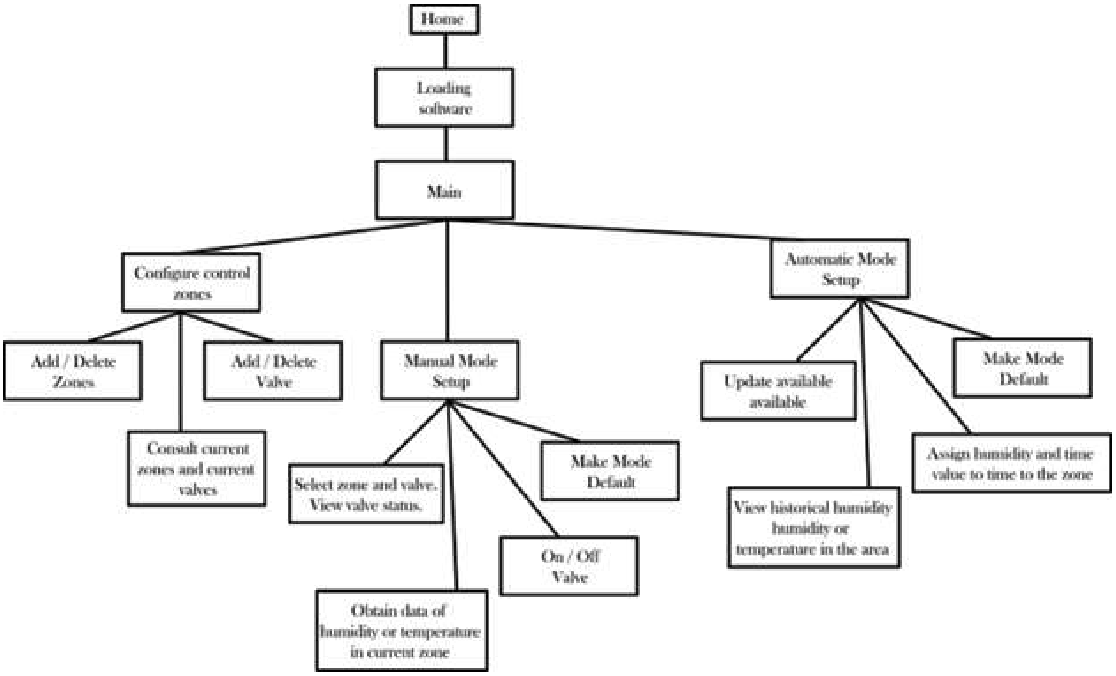
Figure 10. Firmware for hub transceiver node.



Source: Own elaboration

On the other hand, a desktop GUI has been developed in Python programming language, on the Rapsbian operating system of the Raspberry Pi card, whose main function is to be the HMI between the end user and the IoT system, providing features such as automatic mode, manual mode for irrigation management, as well as the generation of graphs and statistics in real time. The GUI navigation diagram can be seen in Figure 11.

Figure 11. GUI for manual process control.



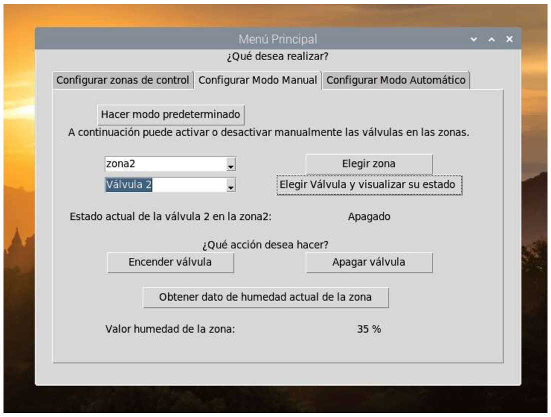
Source: Own elaboration

Results

Once it has been decided the different materials and components to be used in the IoT architecture, it was established all the connections of the different system's tools. For this, a prototype of an irrigation system was made, which is managed through the control action of solenoid valves and can be activated or deactivated both manually and automatically. Each operation mode has an associated programming and defines the system behavior to perform the desired action (all the software has been designed in Spanish language, since it is an application for small and medium producers in Colombia).

Manual mode allows the user to make a real-time change of the valve status in field, as well as to obtain a measurement from environmental humidity sensor of a specific zone at any time (see Figure 12).

Figure 12. GUI for manual process control.



¿Qué desea realizar?

A continuación puede activar o desactivar manualmente las válvulas en las zonas.

zona2

Válvula 2

Estado actual de la válvula 2 en la zona2: Apagado

¿Qué acción desea hacer?

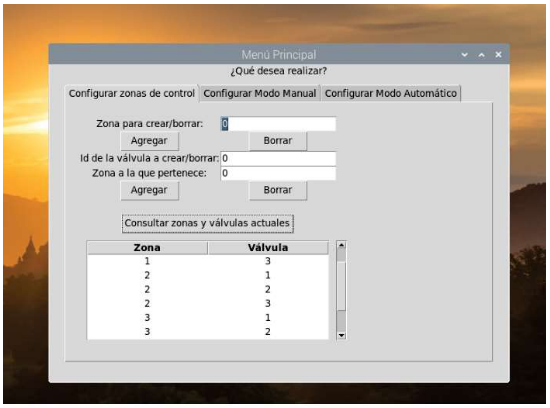
Valor humedad de la zona: 35 %

Source: Own elaboration

Automatic mode, on the other hand, has the ability to activate or deactivate the valves according to sensor readings in each zone. The valves remain active until the system identifies the right humidity, at this point the valves close again. In this case the user does not participate, and it is the system itself that performs the control actions, according to the error associated between the reading and the reference humidity value that is defined by the user (see Figure 13), who has the power to change this value when required. Likewise, the GUI also allows the user to establish how often he prefers to receive humidity data -by zone- at his base station, in order to store the ambient humidity histories for each zone, in order to make subsequent adjustments according to this information.

In addition, the user has another display tab where he/she can enter the crop zones and add control valves. The user can not only enter these values, but also delete these records at any time (see Figure 14). A table has been added for displaying all the zone and valve data, which can be updated at any time by clicking on the <<Consult current zones and valves>> (in Spanish: consultar zonas y válvulas actuales) button.

Figure 13. GUI for automatic process control.



¿Qué desea realizar?

Zona para crear/borrar: 0

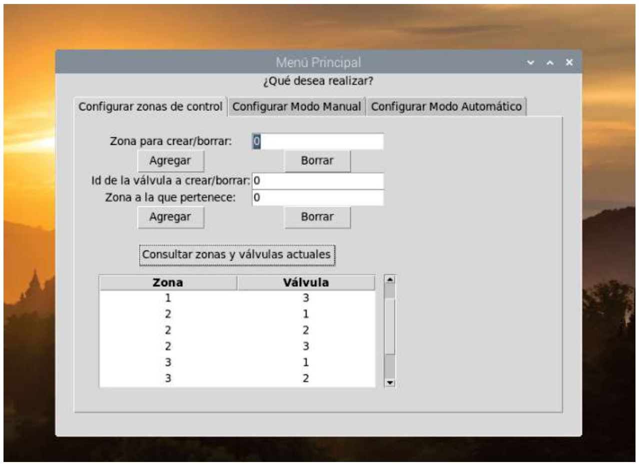
Id de la válvula a crear/borrar: 0

Zona a la que pertenece: 0

Zona	Válvula
1	3
2	1
2	2
2	3
3	1
3	2

Source: Own elaboration

Figure 14. GUI for adding and deleting crop zones and valves.



¿Qué desea realizar?

Zona para crear/borrar: 0

Id de la válvula a crear/borrar: 0

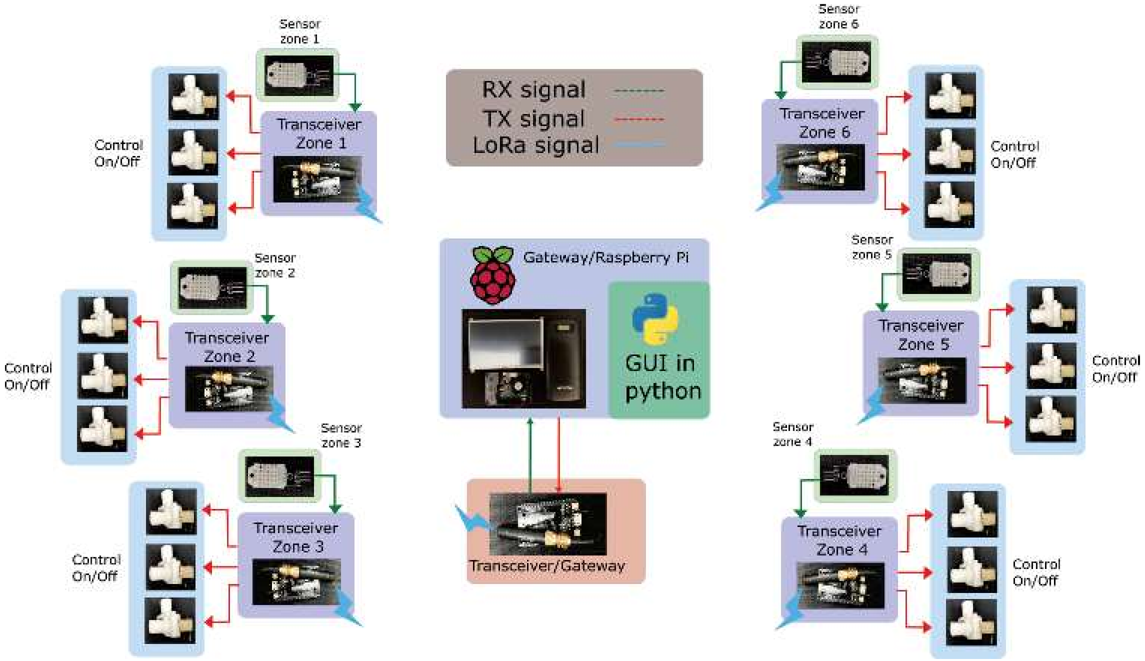
Zona a la que pertenece: 0

Zona	Válvula
1	3
2	1
2	2
2	3
3	1
3	2

Source: Own elaboration

To obtain wireless communication between base station and field nodes, an IoT architecture was proposed with the design shown in Figure 15, where the number of nodes, final control elements, sensors and data transmission signals involved in the process can be distinguished. The diagram shows that the signals indicated with a blue lightning bolt are the wireless transmission through the LoRa protocol, the red signal within each zone node indicates data transmission signals from the TTGO board to the irrigation control valves, and the green signal indicates the reception signal of the data from the DHT22 sensor on the TTGO board. The topology of network proposed in this architecture is show in Fig 8.

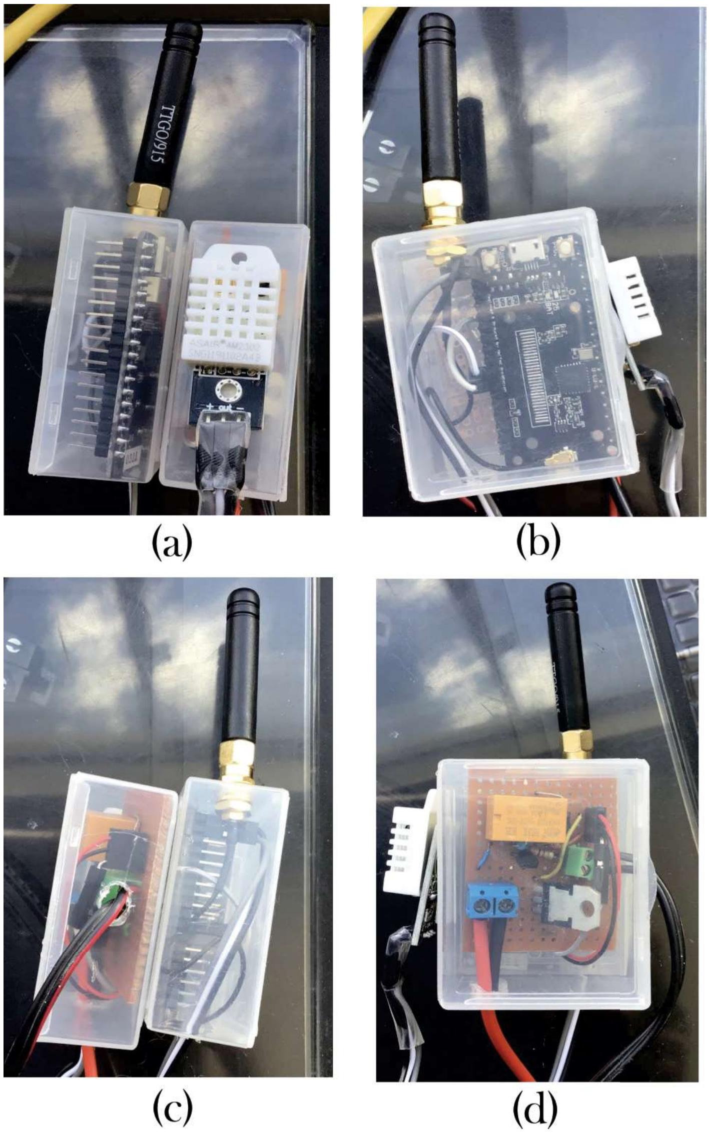
Figure 15. Proposed IoT architecture for irrigation system design and wireless control.



Source: Own elaboration

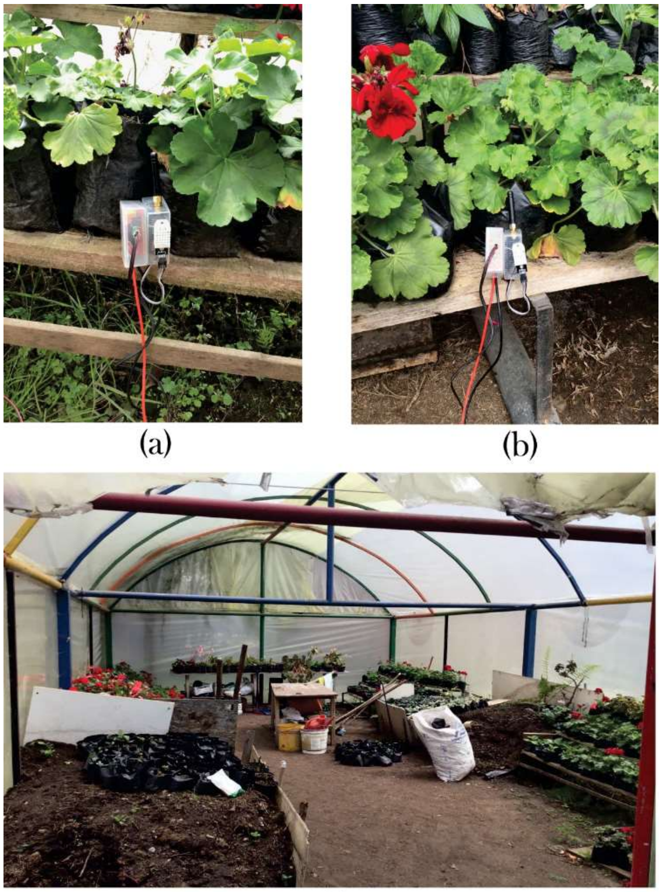
Based on the proposed architecture, the assembly was carried out with the chosen materials, network infrastructure and proposed firmware. The field node prototype can be seen in Figure 16 and 17, which shows the power supply with a VRLA battery and a solar panel, as well as the connection with three valves and their control circuit, the TTGO development board as a transceiver node, its ambient humidity sensor, and an antenna for data transmission.

Figure 16. Test node with sensor, antenna, TTGO board and final control element circuit and power coupling. (a) Right side, (b) front side, (c)left side, (d) back side.



Source: Own elaboration

Figure 17. Prototype in field test. (a) Prototype in zone 1 where tests were obtained, (b) prototype of zone 2, (c) greenhouse where tests were performed.


(a) (b)

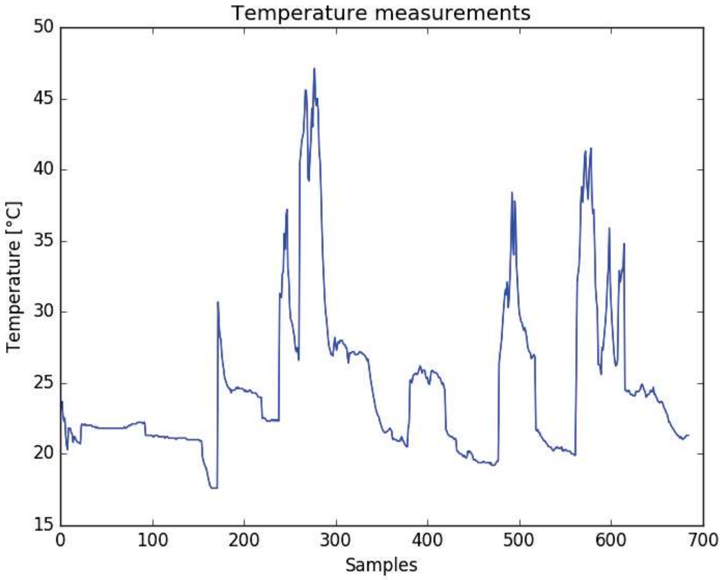
(c)

Source: Own elaboration

Finally, a simulation of a real process was validated with static tests, where a real crop is not read, but simulated with an ambient condition in pots with several plants in a greenhouse. Also, some valves have been simulated with LED diodes instead of solenoid valves, having in each zone at least one real valve, and two other actuators emulated with LEDs. The tests have been carried out for a total time of three weeks in the Universidad de San Buenaventura (Bogotá, Colombia), in order to evaluate the operation of both manual and automatic modes.

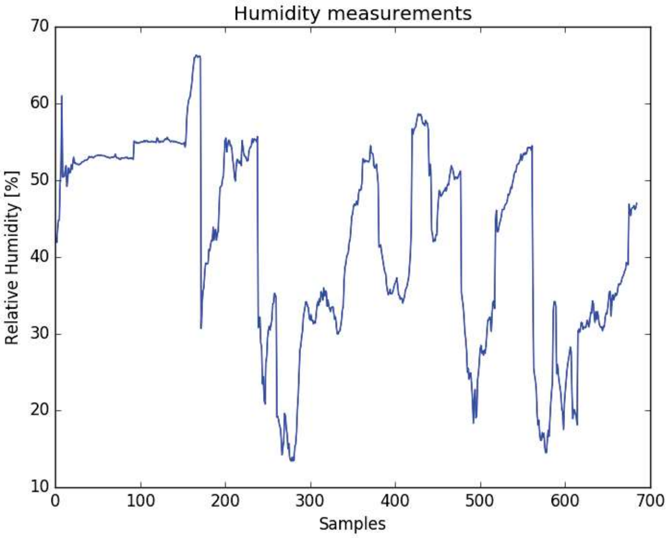
In order to show that humidity changes are also consistent with changes in temperature and time of day, the temperature data from the DHT22 sensor was taken together with the ambient humidity data. The test site was the city of Bogota, Colombia, whose altitude is 2640 m.a.s.l., has an average temperature of 13.1°C, and the relative humidity ranges between 77 and 83%, although in the months of July to September the humidity tends to decrease. The data collected in zone 1 can be seen in Figure 18, 19 and 20. All Figures have been generated through python software.

Figure 18. Temperature data obtained in zone 1. The tests obtained returned a total of 684 measurements between August 28, 2021, and September 17, 2021.



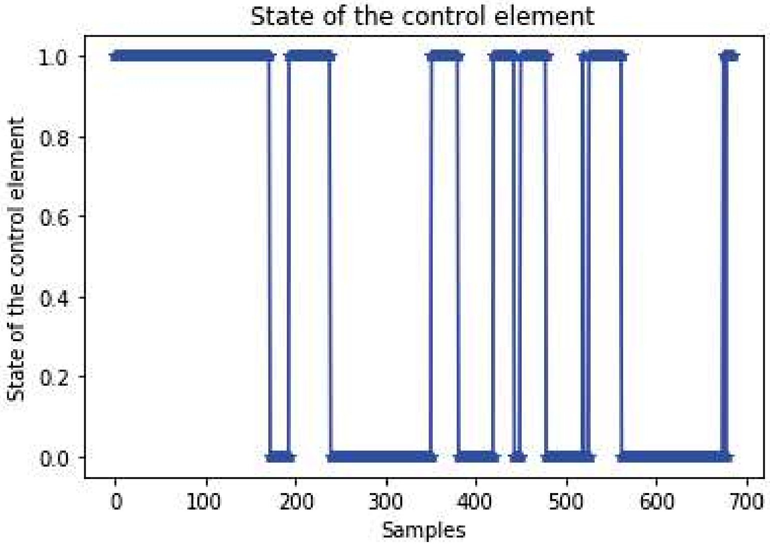
Source: Own elaboration

Figure 19. Humidity data obtained in zone 1. The tests obtained returned a total of 684 measurements between August 28, 2021, and September 17, 2021.



Source: Own elaboration

Figure 20. Data obtained from the condition of the control element in zone 1. The tests obtained returned a total of 684 measurements between August 28, 2021, and September 17, 2021.



Source: Own elaboration

Figure 17 and 18 show the correct operation of the wireless communication through the LoRa protocol from the transmitter node to the concentrator. All the information was collected through the Raspberry Pi with the designed software and stored through a database in MariaDB. Likewise, Figure 19 shows the report of the activation or deactivation status of the power circuit that generates the water flow through the solenoid valve, which was simulated with LEDS for these tests, although a real valve was also left in connection during some days of the tests to demonstrate its correct operation in the field.

Discussion

One of the differences between this project and similar designs or proposals submitted by other authors in the state of the art, is its ability to have a centralized information server that does not depend on cloud connection, largely because it is a development designed for specific tasks, immediate management, and that works for small and medium producers in isolated rural areas or regions, where a network infrastructure either mobile or fixed has very high costs, or there is no infrastructure at all.

In this case, the FARMNET [20] application allows to have a master station through Raspberry Pi, similar to the one shown in the results, in order to obtain data through GSM technology, which makes a clear difference compared to the server used in this project, since LoRa technology was implemented.

On the other hand, the Agrinex project [16] also used a data reception device with a Raspberry Pi, based on an nRF24L01 module, centralizing all data through a web application, and not a desktop application, as is the case of the server proposed in this paper.

Another feature is the technology used in platforms for sending field data. It was found that other authors mostly use modules in ISM free band [9, 11, 26, 13, 14, 15, 16, 21, 23, 24, 25], due to their low energy consumption capacity and portability. This project evaluated the protocol and technology suitable for this application, which has led to the choice of LoRa technology, which is used in other specific projects for sending data due to its scope for applications in rural areas [11, 15, 26, 27, 28].

Regarding the development boards for reception and transmission nodes, there is a common denominator around those simple cards such as Arduino or ESP32, largely because of their ease of programming, their features that fit the crop irrigation requirements, and their technical specifications that make them ideal candidates for these developments.

These projects involve data collection from temperature, humidity, or rainfall sensors around the crop area for decision making [13, 20], as well as applications where there is an infrastructure to control the opening or closing of field valves, based on the information collected from the following projects [9, 10, 23, 24, 25, 26, 11, 12, 14, 15, 16, 19, 21, 22]. The designed system was based on several of the previous initiatives, taking different features and involving not only data collection, but also the interaction between Human-Machine, in order to have a more comfortable relationship between the producer and his/her crop. Therefore, each of the layers of the IoT infrastructure for crop irrigation process was established as follows:

- First, a perception layer integrated by the field sensors that are fundamental (a DHT22 humidity and ambient temperature sensor was deployed) and the final control elements that are instruments to maintain optimal process conditions (with a power stage involving a solenoid valve and its power supply with battery and solar panel).
- Second, the network layer, which involves data transmission using LoRa technology with very low power consumption and sending information at specific times set by the user.
- Finally, the application layer, consisting of user interaction with an interface and a data server, so that the producer can manage decisions based on real-time data taken directly in situ.

Now, last but not least, something that stands out in this design proposal is the system's ability to self-manage itself from solar panels and rechargeable batteries, which makes it possible not only to consume less energy (which is one of the features that causes difficulties in isolated areas with no electrical infrastructure) but also to promote a change in agricultural developments to mitigate climate change, in order to control water consumption as a fundamental and necessary resource that should not be wasted.

Therefore, as in other researched projects, it has a power supply system with non-conventional energy (solar panel). Likewise, it enables a technological opening to the farmer to enhance his field work, providing tools to produce in a responsible and competitive way compared to others, as in the case proposed by [26] in the region of Xinjiang - China.

Finally, regarding the economic feasibility, we have estimated the costs associated with Table 5, which determines the approximate cost for the prototype used per node in the field, and including the central server with the Raspberry Pi, thus generating an overall budget to consider and compare with other existing solutions on the market.

Table 5. Economics feasibility of the final prototype.

Element	Quantity	Unit Price (COP)	Total Price (COP)
Kit Raspberry Pi 3B+. Included: board, case, SD Card, adapter, cables.	1	291.550	291.550
TTGO LoRa32 V1.0.0. Included: two boards, LoRa antenna.	1	95.961	95.961
Voltage Regulator LM 2596 Dc-dc	1	5.000	5.000
Battery 12v 7.5ah O 7,5ah Fulibatteri	1	54.000	54.000
Powerbank ADATA	1	85.000	85.000
Jarrett Solar Panel 12w 12v Photovoltaic	1	59.900	59.900
Relay Module 1 Channel 5v Optocoupled Low/high Level	1	8.000	8.000
DHT22 sensor	1	23.000	23.000
1/2" Electromagnetic Solenoid Valve 12v	4	30.000	120.000
Total prototype			742.411

Source: Own elaboration

The final prototype, as shown in this work, had an approximate cost for a single node including the server between USD 190 and USD 195.

Conclusions

This paper developed a wireless network design of sensors and actuators for an irrigation process, using Internet of Things tools. The design included different elements of free use Software and Hardware, encouraging the development of applications through low-cost technologies for small or medium field producers. The proposal focused on the Internet of Things was based on the 3 layers of an IoT infrastructure, as most authors agree: perception layer, network layer and application layer.

On the other hand, with the worked decision-making algorithms for selecting software and hardware tools, the appropriate devices with greater economic viability for the system were determined. The above in order to be accessible to people of low economic resources, by not depending on a traditional infrastructure of communication networks for data transmission, as well as allowing data to be stored in real time with immediate access to it, in order to make decisions based on such information.

Finally, the proposed design was deployed, generating some readings in real time with the proposed infrastructure, sending data bidirectionally, and allowing control of the valves connected by zone, and providing both manual and automatic management of the functions provided to the user, focused on taking moisture and temperature field data, and sending the valve opening or closing signal to the field node wirelessly.

It was possible to contrast that, to the research question of which is the best IoT infrastructure to improve irrigation systems and optimize resources, the tools on the market are diverse, and depends exclusively on the scope and the specific use required in production, so that this prototype can adhere to small production needs and does not require a large number of inputs for the maintenance of small extensions.

Acknowledgement

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