# UTMACH

## FACULTAD DE INGENIERÍA CIVIL

## CARRERA DE TECNOLOGÍAS DE LA INFORMACIÓN

# Implementación de una red en malla basada en el protocolo ESP NOW para un sistema domótico

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# Mesh ESP Now

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# Secure home automation system based on ESP-NOW mesh network, MQTT and Home Assistant platform

J. Cujilema, G. Hidalgo, D. Hernández-Rojas, and J. Cartuche,

***Abstract*—Home automation allows the interconnection of electrical devices through efficient communication protocols. In order to achieve correct operation, it's necessary to improve the communication and security of the devices that make up the network. Among the main difficulties faced by the systems are communication problems and security problems. In this context, in this work we have developed a mesh network with the ESP-NOW communication protocol that has allowed the correct implementation of a home automation system with commercial IoT devices. After the tests performed, it has been confirmed that the proposed network has had an average latency of 152 ms in the scenario farthest from the Gateway with a low average packet loss. It has been confirmed that the proposed network can be implemented and improve the performance of a home automation system with commercial devices. In addition, it's a secure network as it has data encryption in both the MQTT Broker and ESPNOW.**

***Index Terms*—ESP-NOW, Smart Home, Mesh Network, Domotic System, MQTT, Home Assistant.**

## I. INTRODUCTION

The internet of things has had a very significant breakthrough due to the great impact it is having in the many areas it has been implemented [1], [2], [3]. According to [4], IoT continues to have an incessant development because to several factors such as the progress of technology, the production value of products and related services. Such progress has allowed to generate a great development in the field of home automation, which is why it is currently positioned as a feasible technology for internal management and home energy efficiency [5], [6], [7], [8].

One of the IoT application domains is home automation [9], where it is feasible to remotely control household appliances, as well as to monitor electrical variables, temperature, humidity, among others [10].

However, the benefits that home automation offers may be limited to a certain group of people due to difficulties such as implementation, maintenance, high latency communication protocols and very low network coverage. In this context, communication between devices is a fundamental part of a home automation system, so the choice of a communication protocol must take into account the needs and the possibilities that adapt to them [9], [11]. Sharma and Kumar [12] mention that communication protocols must provide agility, security and reliability without affecting with IoT constraint devices. As [12] points out, here is a wide variety of wireless communication protocols, some of them are: BLE, Zigbee, Bluetooth, ESP-MESH, ZWave, among others, which are implemented according to their application. Each protocol has characteristics that differentiate them, for example BLE is applied for short distance communication, unlike Zigbee that allows a longer range deployment, therefore, it is of great importance to consider its possible application, structure, latency and energy efficiency when selecting a protocol to be used in an IoT project [12], [13].

As stated T. Ngoc, S. Tran, B. Nguyen [14], in 2018, a point-to-point protocol by the name of ESP-NOW emerged, the same protocol that was released exclusively for the ESP32 device. This protocol does not require routers to form a network, instead it proposes a point-to-point network and low-power communication between several devices.

The ESP-NOW communication protocol is currently an efficient and versatile protocol when sending data, since it is capable of sending data over long distances with very fast transfer speeds. It is currently being implemented in many areas such as home automation, agriculture, robotics, etc. [15], [16].

ESP-NOW is a protocol designed exclusively for IoT, and it constitutes, very good, as a data transfer protocol for smart homes, since it does not require wi-fi connection, with low latency.

This work proposes a Mesh network based on the ESP-NOW communication protocol in order to solve the communication and security problems. For this purpose, an architecture was designed in which the MQTT, Bluetooth Low Energy and ESP-NOW protocols were implemented. Communication between IoT devices was carried out without the need to implement wi-fi externally. An IoT Gateway was created, consisting of a Raspberry Pi and an ESP32. Security was also added to the network through AES encryption technology, as it is currently the most widely deployed and compared to the TripleDES encryption standard, it is approximately six times faster. For the use of ESP8266 boards, the network should not

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carry AES encryption due to its limited capabilities [17].

The document is organized as follows: Section II presents the work re,lated to this paper, Section III presents the ESP-NOW communication protocol, Section IV describes the operation of the ESP-NOW mesh network in a home automation system, Section V demonstrates the performance of the proposed network through experimental tests; Section VI presents the analysis of the results obtained in the performance tests; and finally, Section VII with the conclusions of the work carried out.

## II. Related Literature

This section shows some works related to the development of home automation systems with different communication technologies, emphasizing those that have used ESP-NOW.

In the work Radhanand's et al. [18] implemented a distributed automation home automation scheme using ZigBee and MQTT protocols [19], as results obtained that the messaging format of the Zigbee protocol is very rudimentary and is not suitable for adding more nodes.

Wen and Wang [20] designed a Raspberry Pi based smart home environment that receives network traffic from all nodes; data such as temperature, humidity, light intensity, and so on. The area of health is a factor that has been taken into account in home automation systems, since through the use of these you can get to analyze the activity of the residents of the home, so in the work of [21] a home automation system solution that provides a complete analysis of the users, including health data and information of the location and body activities that they perform is offered.

In [22] they propose the development of a home automation system consisting of a master ESP32 that is responsible for receiving messages from a mobile application via wi-fi to send them in encrypted form to 6 ESP32 modules through ESP-NOW. In this system the nodes cannot communicate with each other, so they depend on a master device to communicate with the application. That is why in our mesh network we used broadcast messaging so that all nodes can send messages to each other using AES (Advanced Encryption Standard) encryption, also, it is not limited only to ESP32 boards so Lopy4 devices were also used.

In the work of [23] they propose a group home monitoring system in which they used ESP8266 boards, wi-fi and the ESP-NOW protocol. This system consists of four parts the ESP-NOW emitter, the ESP-NOW receiver, the gateway and the server. Using the ESP-NOW protocol, the senders send messages to the receiver, which is serially connected to the gateway, and then send these messages to the server and display them on a dashboard. The serial connection between the receiver and the gateway can be slow because the data is transmitted bit by bit. In this work we propose a special gateway that consists of a Raspberry Pi and an ESP32 which communicate via BLE (Bluetooth Low Energy) allowing faster communication. This gateway receives the messages from the ESP-NOW mesh to send them to the Home Assitant platform and vice versa.

A work done by [24], proposes a temperature monitoring system for hydraulic cylinder in which an ESP32 sends data from temperature sensors by ESP-NOW to a web server to visualize them in a dashboard. This system presents a simple unidirectional architecture, so this work proposes an improvement with a bidirectional communication in which all nodes can communicate with each other and be monitored with a watchdog mechanism.

There is a library called ESPNOW flooding mesh that proposes an ESP-NOW mesh network with an unlimited number of slave nodes, but only one master node. It uses broadcast messaging with a TTL (Time To Live) mechanism to avoid loops in the network. It also uses encryption with AES [25]. However, this library presents performance problems due to the fact that it has not received updates.

The m2mMesh library also offers a mesh network with ESP-NOW between ESP8266, ESP8285 and ESP32 microcontrollers. This library is still under development, therefore, it has several problems to solve, among them one of the most important is that it does not have data encryption, so it is recommended not to implement it for sending confidential information [26].

Mesh networking is a topology that will provide benefits such as communication between all nodes in the network, without relying on a central node to receive network traffic, if one node fails the network is re-organized so that it continues to function. As [27] expresses, mesh networks would be very beneficial for smart homes and smart cities, as connectivity and reach would be greatly improved, without the need to upgrade the network infrastructure.

Home automation, although it has provided several benefits to the comfort of users at home, its implementation is still complicated. This is due to several factors such as the budget of the devices, lack of knowledge, areas of difficult access or with poor coverage, the security of the data sent through the network, among others [28]. In Almusaylim and Zaman's work [29] they make mention of smart home security issues such as communication eavesdropping, denial of service (DoS) attacks, physical attacks either to remove sensors or remove nodes, alteration of message contents, etc.

## III. ESP-NOW Protocol

ESP-NOW is a communication protocol developed by Espressif company. It allows to transmit short packets using the MAC address of ESP32 or ESP8266 devices. The ESP-NOW protocol uses the IEEE 802.11 standard [30], [31]. According to [32], this protocol reduces the five layers of the OSI model to a single layer as shown in Fig. 1.

This protocol offers several advantages, which are described below:

- **Fast response:** devices after power-up can transmit and control data from other paired devices directly, giving responses with millisecond speeds.
- **Low energy consumption:** by reducing the five layers of the OSI model to a single layer, power consumption is reduced.
- **Good compatibility:** a device that is connected to a faulty router or the network is unstable, can perform fast and stable communication using ESP-NOW.


Fig. 1: ESP-NOW Layer Model [32].

- **Improved range and reception:** registers a callback for sending ESP-NOW data.
- **Multilayer control:** with ESP-NOW you can send unicast and broadcast messages to control certain devices.

### A. ESP-NOW API

The functions required for the ESP-NOW implementation can be found in the ESP-IDF library API. Some of the most commonly used functions are listed below:

- **esp_now_ init:** to initialize the ESP-NOW protocol.
- **esp_now_set_pmk:** is used to set the PMK key.
- **esp_now_add_peer:** is used to add or pair the devices to which the data will be sent.
- **esp_now_send:** sends data to the paired devices. This function will return ESP_NOW_SEND_SUCCESS, if the data is successfully received by the paired target device. Otherwise, it will return ESP_NOW_SEND_FAIL.
- **esp_now_register_recv_cb:** registers a callback for receiving ESP-NOW data which is called when the device receives ESP-NOW messages.
- **esp_now_register_send_cb:** registers a callback for sending ESP-NOW data.

## IV. Mesh ESP-NOW

This section contains a description of how the ESP-NOW mesh network works in a home automation system.

### A. Network architecture

The network proposed in this work uses the MQTT, Bluetooth Low Energy (BLE) and ESP-NOW protocols, as shown in Fig. 2.

The ESP-NOW mesh nodes consist of one ESP32 and two Lopy4 nodes, as shown in Fig. 2. These nodes receive and send data via ESP-NOW using a structure that contains a grouping of data consisting of a list of the message path, the destination node identifier, the data with the node ID and other variables such as humidity or sensor temperature, as shown in Fig 3. All these data are sent to an MQTT broker through the gateway either to send data to the IoT platform or from the IoT platform to the nodes of the mesh network.

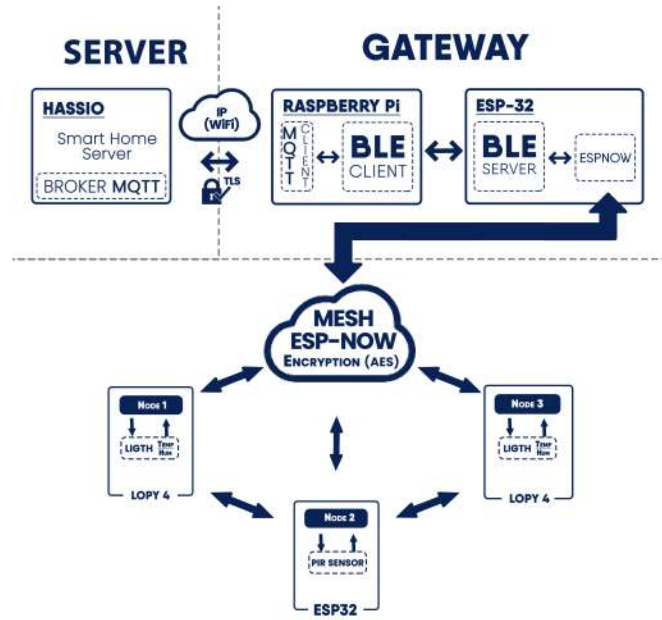


Fig. 2: Proposed architecture of the ESP-NOW Mesh.

| Destiny Id (2 bytes) | Routes (Array10 bytes) | | | Data (16 bytes max) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Node 1 | Node 2 | .... | Id node | Var 1 | Var 2 | .... | Var N |

Fig. 3: Structure of the ESP-NOW message.

The MQTT (Message Queuing Telemetry Transport) protocol is an ISO standard, which is based on a publish/subscribe mechanism, designed for remote connections between nodes with reduced memory capacity [33], [34]. It allows the transmission of one-to-many client messages, which makes it a very effective protocol in the IoT area. Clients communicate through topics, which perform the function of private communication channels [35].

Bluetooth Low Energy (BLE) is a short-range wireless technology that for many IoT developers has been considered one of the best options because it is cross-platform, has been integrated into smartphones, its power consumption is minimal, it is robust and efficient, among others [36], [37].

### B. Sensor and actuator layer

It can consist of microcontrollers based on ESP32, in our case we have used commercial hardware platforms such as Lopy 4 and ESP32 development kit itself. The sensors used are DHT11 to measure the temperature and humidity of the environment, and a PIR sensor to detect motion. The actuators are relays that control the switching on and off of light bulbs.

A technique similar to message flooding was used to transmit messages between the nodes of the ESP-NOW mesh. The nodes make use of a broadcast address that allows messages to be transmitted to all nodes. To prevent the network from falling into a loop, a list of routes that is transmitted in each message was used, so that each node checks if its ID is in the list to avoid retransmitting the same packet several times, as shown in the Algorithm 1.

Messages sent between nodes are encrypted using AES technology [17], [38], which requires a key to be defined in each node. Without this key, a node will not be able to encrypt or decrypt the messages it sends or receives. The maximum data size that can be encrypted is 16 bytes. All these algorithms are available in our Github repository [39].

**Algorithm 1** Node algorithm

```
Start ESP-NOW
if Received a message? then
    if Is the message for this node? then
        Execute another action
    else
        Check the list of routes in the message
        if ¿ID is on the list? then
            No re-broadcast
        else
            Add ID to the list
            Re-broadcast
        end if
    end if
else
    Send keep a live every 2 minutes
    Send sensor data every minute
end if
```

*1) Node 1:* For the construction of this node, the ESP32 board was used, which has a 4 MB flash/SRAM memory and is powered with 5 V. This node has connected a DHT11 sensor that measures the humidity and temperature of the environment, this sensor is connected via the GPIO 4 pin and is powered with 3 V. It has an actuator that is a relay which turns on a light bulb, this actuator is connected to the GPIO18 pin and is fed in the same way with 5V. Finally, as shown in Fig. 4 and 5 an OLED Display that shows the data from the DHT11 sensor is also connected.

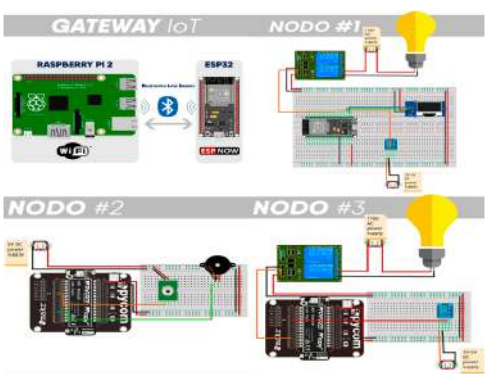


Fig. 4: Node 1,2,3 and gateway diagrams.

*2) Node 2:* Node 2 consists of a Lopy 4 that runs on the Espressif ESP32 chipset, has 4 MB of RAM, is powered by 5 V and supports the 802.11 standard. This node has a PIR sensor that can be calibrated by distance and reading time and a buzzer actuator, which is activated when the digital output of the PIR detects motion. These events are sent to the MQTT broker using ESP-NOW through the gateway. The assembly of this node is shown in Fig. 5 y 4.

*3) Node 3:* The operation of this node is similar to node 1, with the difference that the Lopy 4 board is used and the pin layout varies, as shown in Fig. 5 and 4. For the DHT11 sensor the connection is made to the GPIO 24 pin and for the relay to the GPIO 16 pin.

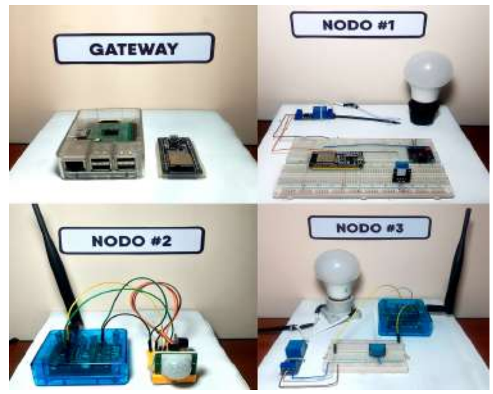


Fig. 5: Prototypes for nodes 1,2,3 and gateway.

### C. Gateway IoT

For the development of this gateway, a Raspberry Pi and an ESP32 that communicate using BLE technology were used, as shown in Fig. 4 y la Fig. 5.

The reason for the realization of this gateway is due to the transmission channel conflict between wi-fi and ESP-NOW, forcing the nodes to use the same transmission channel of the wi-fi network, which limits adding nodes outside the coverage of the wi-fi router or AP (Access Point).

The ESP32 is responsible for receiving data from the ESP-NOW mesh to send to the Raspberry Pi via BLE, where the Raspberry acts as the client and the ESP32 as the server, as shown in the Algorithm 2. The Raspberry uses the Node-RED visual programming tool [40], [41], to connect as a client to the BLE server. The communication between the MQTT broker and the Raspberry is encrypted with TLS to add further security to the network. Fig. 6 shows the flow used to receive data from the MQTT broker and send it through BLE to the ESP32.

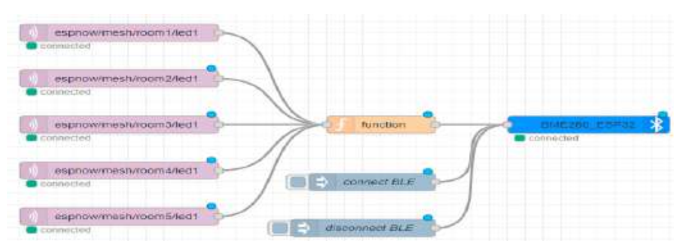


Fig. 6: Node-RED flow to receive data from MQTT broker and send it to BLE server.

The data received by the BLE server is sent to the MQTT Broker using a switch type node that is responsible for parsing the data to send it to its respective topics, as shown in Fig.

**Algorithm 2** Gateway algorithm (ESP32)

```
Start BLE Server
Start ESP-NOW
if Received message? then
    if ¿BLE? then
        Encapsulate ESP-NOW
        TX-ESP-NOW
    else
        RX-ESP-NOW
        Encapsulate BLE
        TX-BLE
    end if
else
    Execute another action
end if
```

7. This flow must first connect to the BLE server and then activate the notify node to receive the data.

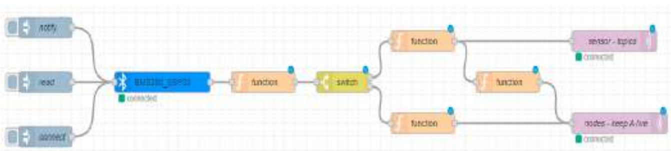

Fig. 7: Node-RED flow to receive messages from the BLE and send them to the MQTT Broker.

For the local administration and monitoring of the nodes connected to the network, a dashboard was created in Node-RED with a list where the node number and its on or off status are displayed, see Fig. 8. It runs on the Raspberry Pi integrated in Hassio.

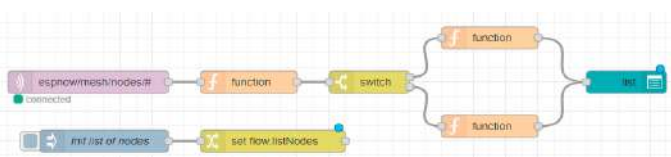


Fig. 8: Flow in Node-RED that lists the nodes connected to the network.

### D. Smart Home Server

For the home automation system server, the Home Assistant (Hassio) platform was used because it is free software and allows home automation [42]. Hassio has an extensive list of add-ons, including Mosquitto which was used as an MQTT broker to receive and send data in json format such as sensor data or activate actuators. This software has its own dashboard where the received data such as temperature, humidity and motion detection are displayed, as shown in Fig. 9. In addition, the user can control the switching on and off of lights or other devices that have been configured.


Fig. 9: Dashboard in Home Asistant.

The user can configure triggers that are activated when an event occurs or the value of a sensor changes, for example, if the temperature exceeds a set range a notification is sent to the cell phone.

The configurations in Hassio are done through a configuration.yaml file in an easy and fast way, since it does not require complex commands, has good documentation and an active community. In our repository [39] you can find the configurations for the on buttons of the rooms, in this case each switch has a unique ID, a name that will be used in the dashboard, the state_topic that indicates the topic by which it will receive and send the data, the value_template that indicates the value of the data in json format to be taken and finally the on and off states.

On this platform, a watchdog mechanism has been implemented to list and observe the status of the active nodes in the ESP-NOW network. In Hassio each node has a card associated with the status and a timer with a duration of three minutes that is reset every time a node sends a message, if a node does not send a message within that time the card is deactivated indicating that the node is inactive, as shown in Fig. 10. For this, the nodes are scheduled to send Keep Alive messages every 2 minutes.

The cards must be manually configured by the network administrator, which is why a list was added to the dashboard which is updated in real time with all the nodes that are active in the system.

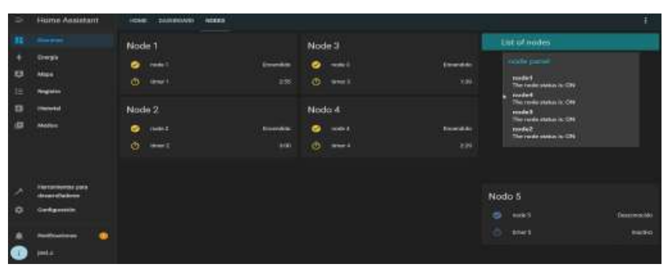


Fig. 10: Monitoring the status of nodes in the ESP-NOW network.

## V. Experiments

This section describes the test scenarios of the proposed mesh network operation, for this purpose two additional nodes were added to the mesh to achieve five test scenarios. The Table I shows the tests that were performed in this work and Fig. 11 the location of the nodes in a real scenario, which were placed similar to a typical home distribution and that allows replicating the best and worst case scenarios.

TABLE I: Tests for the proposed mesh network

| Tests | Objective | Metrics |
|---|---|---|
| Latency | Measuring the data transmission rate | Time |
| Security | Demonstrate network security | Encrypted data |
| Packet loss rate | Measuring the rate of packets lost in the delivery of data | Number of packages lost |

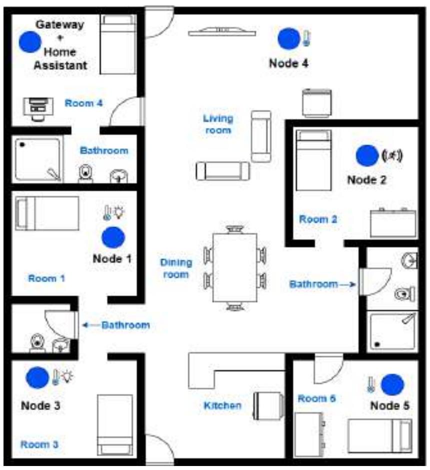


Fig. 11: Location of nodes in a typical house.

The proposed scenarios for testing the mesh network in the home automation system are described below. In each of the scenarios, the objective is to measure the latency time and the packet loss rate.

- Scenario 1: In this scenario the distance between the gateway and node 1 is 5.35 m, having 2 walls as obstacles.
- Scenario 2: As a second test scenario, node 2 and the gateway were placed at a distance of 7.75 m, with 2 walls as obstacles.
- Scenario 3: This test scenario has the gateway and node 3 at a distance of 10.35 m and with a number of 4 walls.
- Scenario 4: This scenario will take place between node 4 and the gateway, with a distance of 5.15 m, with an obstacle wall.
- Scenario 5: This last scenario will take place between node 5 and the gateway at a distance of 12.10 m, having several obstacles.

## VI. Results Analysis

The results obtained from the tests performed in the scenarios indicated in the previous section are shown below. Table II shows the latency results of sending messages from the nodes to the Gateway, obtaining a minimum, maximum and average time for the five scenarios expressed in milliseconds.

TABLE II: Node latency test results to the gatewayy

| | Minimum (ms) | Maximum (ms) | Average (ms) |
|---|---|---|---|
| Scenario 1 | 5 | 725 | 67 |
| Scenario 2 | 12 | 1.961 | 150 |
| Scenario 3 | 1 | 636 | 67 |
| Scenario 4 | 12 | 924 | 91 |
| Scenario 5 | 1 | 1.270 | 152 |

Similarly, Table III presents the result of the tests performed by sending 100 messages every 30 seconds from the gateway to the different nodes and from the nodes to the gateway. Fig. 12 shows considerable latency in scenario 2 and 5 due to the fact that these nodes are located far from the gateway and obstacles influence the transmission of messages.

The network message sending and receiving times are fast, with a maximum around 1 second and an average of 152 ms in the 12 m scenario, compared to other home automation work such as in [43] where similar distances result in 500 ms. Based on these results, the ESP-NOW protocol has some advantage in terms of message sending speed.

TABLE III: Gateway to Node Latency Test Results

| | Minimum (ms) | Maximum (ms) | Average (ms) |
|---|---|---|---|
| Scenario 1 | 0 | 350 | 80 |
| Scenario 2 | 0 | 536 | 35 |
| Scenario 3 | 0 | 65 | 18 |
| Scenario 4 | 0 | 248 | 32 |
| Scenario 5 | 0 | 1011 | 58 |

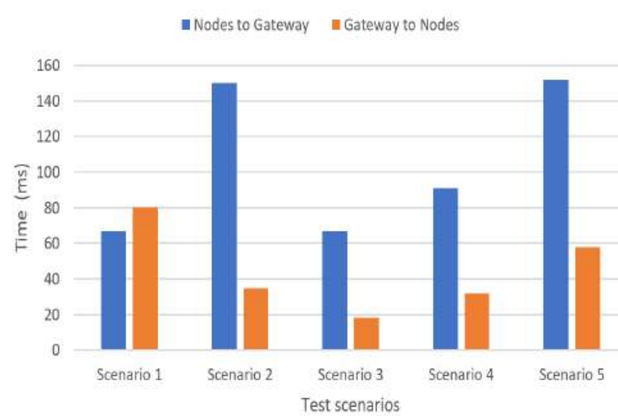


Fig. 12: Packet transmission latency.

As can be seen in Fig. 13, scenario 5 shows a very significant loss of packets in sending messages from the node to the Gateway, this is due to the distance between them, but the opposite happens in the other nodes, since from a total of 200 messages sent every 30 seconds the loss of packets is minimal, also 200 messages were sent every 10 seconds from the Gateway to the nodes, in scenario 4 there was a loss of 24 packets and in scenario 5 there was a total of 56 packets lost, this happens due to the types of existing obstacles such as aluminum doors and beds and concrete walls, another reason is for the reason to the fact that the messages were sent under a short period of time and the message flooding technique used in the mesh, which causes the sending of messages to be duplicated.

The proposed mesh network obtained a total of 86.85% of packets successfully received out of 200 messages sent every 30 seconds, compared to other solutions such as [44] which obtained a result of 87.27% out of a total of 60 packets, the values are similar taking as a variant the number of packets sent, with ESP-NOW it was possible to send more messages and obtain few losses in some scenarios.

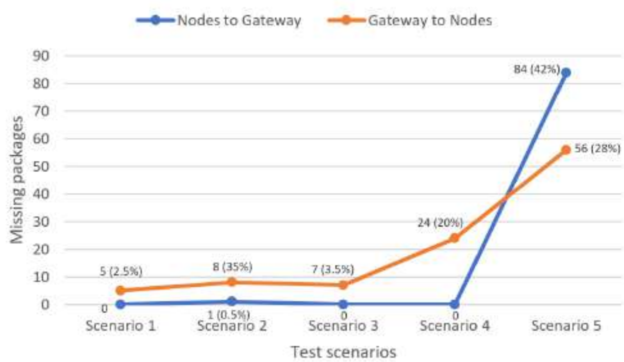


Fig. 13: Lost packet rate.

In the security tests, it can be seen in Fig. 14 that the nodes receive encrypted data thanks to the AES technology and in order to decrypt them a key must be used, otherwise it will not be possible to read or manipulate them. For the MQTT broker the data was captured using the Wireshark tool, Fig. 15 shows that the encrypted data cannot be visualized.


Fig. 14: ESP-NOW mesh data encrypted with AES.

Fig. 15: MQTT data encrypted with TLS.

## VII. Conclusion

A fast and secure mesh network was implemented for home automation systems, independent of the home wi-fi network, therefore, there is no interference between the rest of the home appliances, multimedia devices available in common homes. The ESP-NOW mesh network was integrated into the Hassio home automation platform through a special IoT gateway. A system was implemented to monitor the status of the nodes in the ESP-NOW network in real time by means of a proprietary watchdog system. Data security is guaranteed throughout the system, ESP-NOW ensures robust security on and off the mesh, a security system was implemented with MQTT communication.

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