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Design and Validation of a Wi-Fi Based Active RFID System for Hospital Equipment Management

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Abstract

The Medical Equipment Information and Management System (SIGEM-UV), developed by the School of Biomedical Engineering at the University of Valparaíso, seeks to improve the management of medical equipment through various tools and systems. Among these, the LocDEM module stands out, focusing on the active location of medical equipment using WiFi TAG technology. This project addresses the problem of locating medical equipment in healthcare facilities, which interferes with workflow, is time-consuming, and, in some cases, leads to equipment theft. Although commercial solutions exist, they require specific infrastructure, presenting a significant barrier to entry. The SIGEM-UV WiFi TAG project proposes a solution that utilizes existing WiFi infrastructure, minimizing additional costs. A location system was developed based on a microcontroller connected to a web server with an intuitive user interface. This device, with a smaller footprint and improved autonomy, collects data from nearby WiFi networks and sends it to the server, where it is processed to determine the

location of the equipment. The user interface allows the location to be displayed on a building map, facilitating rapid equipment identification. The main results demonstrate the feasibility of the design and its implementation, as well as the appropriate levels of localization efficiency for hospital environments. This system presents a viable and low-cost alternative for the management and localization of medical equipment in healthcare institutions.

Keywords: Active location; WiFi TAG; medical equipment management; WiFi infrastructure.

Introduction

The Medical Equipment Information and Management System (SIGEM-UV) is a project of the School of Biomedical Engineering at the University of Valparaíso [1]. Its objective is to develop tools and systems that optimize the management of medical equipment, based on the experiences, best practices and recommendations of national and international technical organizations [2].

Specifically, the module proposed in this work, called WiFi TAG, consists of an active device based on a microcontroller that, by analyzing the signal strength received from the WiFi access points available in a hospital facility, can estimate the approximate floor and sector where a specific medical device is located. The devices that typically need to be located are portable devices such as ultrasound scanners, multiparameter monitors, and surgical equipment, which are moved between different pavilions, warehouses, or services within a hospital.

There are commercial solutions such as the "T12s Asset Tag" from Securitas Healthcare [3], the "Beeks Tag" from HDI Global [4], and the "Eye Beacon" from

Teltonika [5] , which primarily use Bluetooth technology. Although these options have low energy consumption, they require the installation of a specific infrastructure, that is, a network of beacons and antennas distributed throughout the institution's premises, which creates a very significant limitation for their implementation, especially in operating hospitals. In addition to Bluetooth, other technologies such as Zigbee, RFID, and WSN (Wireless Sensor Networks) have been proposed for equipment location in healthcare environments. Zigbee and WSN offer networks of interconnected nodes with low energy consumption, but their limited coverage and installation complexity can make them difficult to implement. On the other hand, RFID provides efficient short-range location, but its accuracy depends largely on the installed infrastructure and proximity to readers.

Previous research has explored active localization in healthcare settings using systems such as LAURA, which combines WSNs and wearable sensors to deliver an average localization accuracy of less than 2 meters in 80% of cases [6] . Despite the achieved accuracy, the need for additional infrastructure and implementation complexity remain significant challenges. Another study proposes an efficient angle of incidence (AoA)-based method for indoor localization, using special multi-antenna Wi-Fi access points with known direction. This methodology achieves a localization error of less than 2.5 meters in line-of-sight environments, overcoming some of the limitations of RSSI-based methods, but incorporating the complexity of using special access points and the associated installation costs [7] .

Furthermore, the integration of RFID technologies and sensor networks allows for improved accuracy and robustness in indoor localization. It has been demonstrated

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that the use of a hybrid RFID and WSN system can achieve an accuracy of up to 0.45 meters, significantly surpassing solutions based solely on RFID . [8] However, the implementation of these systems requires a dense infrastructure and high costs, which limits their application in hospital environments.

On the other hand, in a hospital setting, electromagnetic interference and high infrastructure costs limit the application of certain technologies. The use of UHF RFID for medical device localization has been explored, successfully overcoming interference restrictions and ensuring a safe environment for patients [9] . However, implementation in clinical settings still faces significant challenges due to the complexity of the infrastructure and the need to minimize interference to critical devices.

The TAG WiFi project, linked to SIGEM-UV, has made progress in proofs of concept, RSSI (Received Signal Strength Indicator) measurements, and WiFi-based trilateration. However, these initial advances focused on the use of Raspberry Pi-powered devices, which, although useful for performing proofs of concept, are not viable for mass implementation in medical devices due to their large size, high cost, and low autonomy [10] .

In this context, we propose an active location system based on a WiFi TAG, a microcontroller connected to a web server and a user interface. This device stands out for its small size, improved autonomy, and ease of use and installation, requiring only the WiFi TAG, the institution's existing WiFi infrastructure, and a registry of the SSID (network identifier) and MAC (network hexadecimal address) of each available WiFi access point. Unlike commercial solutions based on

Bluetooth or RFID, this system leverages the existing WiFi infrastructure, eliminating the need to implement additional infrastructure, such as beacons or sensors, and significantly reducing costs.

The overall objective of this project is to develop and implement a cost-effective active location system for medical devices based on WiFi TAG technology. Specific objectives include the development and evaluation of the WiFi TAG hardware, the development of the software and web user interface, and the design of a low-power model to maximize the WiFi TAG's autonomy. This approach seeks to provide a more affordable and efficient alternative compared to other location technologies available on the market.

Materials and Methods

This work is an experimental development project, focusing on the design, implementation, and evaluation of an active location system for medical equipment using WiFi TAG technology. The project was carried out in several stages, including hardware selection and configuration, software development, and system integration in a controlled environment. The materials used and the methods employed to carry out each of these stages are detailed below.

How the WiFi TAG Works

The WiFi TAG is an active location tool that relies on the WiFi infrastructure available at the target establishment, without the need for investment in new dedicated infrastructure. Its operation is based on the WiFi TAG itself and a web server that hosts the user interface, the database with WiFi network information,

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and the computational logic for estimating the WiFi TAG's location on the different floors of the facility.

The WiFi TAG directly obtains the battery percentage and its MAC address. Additionally, it collects all nearby WiFi networks with their SSID, MAC, and RSSI signal, connects to an established WiFi network with Internet access, and sends all this data to the Web server. The Web server, on the other hand, is responsible for receiving this information to process and interpret it. Within this interpretation, the server has a user interface where the device to be tracked is selected. Within a floor plan of the building, matches are generated between the MACs read by the TAG and those belonging to the building's WiFi access points (APs). This graphically displays the floor on which the device is located and the WiFi repeaters it is near, as illustrated in Figure 1 .

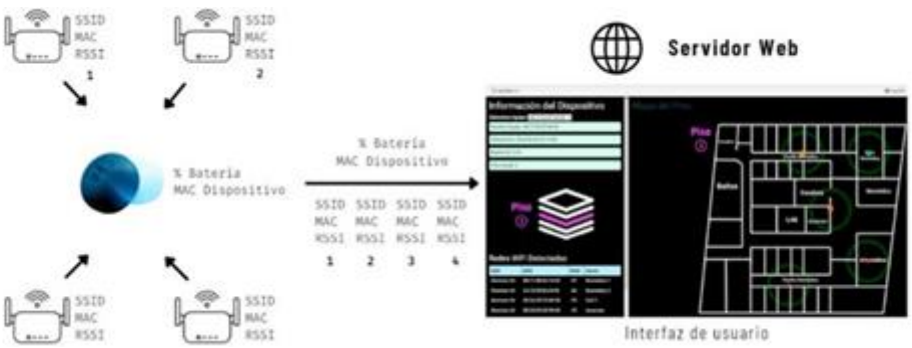

Figure 1 WiFi TAG operating diagram.

Requirements and materials for implementation

For the implementation of this technology it is necessary to take into account the following requirements and materials:

- WiFi TAG with 100% Battery Charge: TAGs were selected in two versions, one with a 500 mAh battery and another with a 2000 mAh battery, ensuring that they were fully charged and with the code updated to connect to the WiFi network defined for the project.

- Available Wi-Fi Network: The implementation was carried out at the School of Engineering at the University of Valparaíso. The "UV Visits" Wi-Fi network was used for connection, and the "UV Students" network was used for MAC analysis. It is crucial to have a corporate connection network with the same name and password on all floors where the Wi-Fi TAG is located.

- Medical Device for Tracking: Although the WiFi TAG is planned to be associated with a medical device or equipment for tracking, in this case, for simplicity, the device was used independently to facilitate its mobility within the building.

- Updated Floor Plans for Each Building Floor: It is essential to have updated floor plans for each floor of the building so that the user can properly position the device within the facility.

- Access Points (APs) per Floor: To ensure proper localization, at least two access points per floor of the building are required. Detection algorithms rely on the RSSI signal of each AP to estimate its position.

- Surveying WiFi MAC addresses of access points: A manual survey was performed for each access point, extracting its MAC address and estimated location relative to the floor plan. For this task, a programmable M5stack Core device was used, which was programmed with a user interface that, upon pressing a button, displayed the available WiFi networks along with their RSSI, MAC address, and SSID on the screen.

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This device is placed near the AP to be analyzed, the button is pressed and the WiFi networks emitted by the AP are recorded along with the aforementioned data. The relevant information of said AP (MAC) is stored in the database, as illustrated in Figure 2 .

Figure 2 M5 stack core used for MAC lifting.

Hardware Selection

The hardware configuration selected for this device arose from the need to reduce the size and power consumption of the initial system based on a Raspberry Pi [10] , which measures 85 x 56 x 17 mm without a battery. Although the Raspberry Pi is useful, its size, cost, and low battery life make it unfeasible for portable medical devices. To address these challenges, the use of a microcontroller was proposed instead of a complex processor like the Raspberry Pi.

Initially, the use of an Arduino with a WiFi module was evaluated. However, more efficient options were identified, such as the Espressif ESP32 microcontrollers. ESP32s are highly versatile, allow for the simple development of IoT projects, and stand out for their small size, low power consumption, and lower price compared to a Raspberry Pi. After evaluating the project needs, it was determined that the ESP32 microcontrollers met the main required characteristics: WiFi connectivity, compact size, low power consumption, lower cost, and the possibility of adding an integrated circuit for battery connection. The research focused on finding a small-format microcontroller that could be placed in a device for an extended period of time, without being invasive to the medical equipment or interfering with its daily use (Table 1).

Table 1 Comparison between different ESP32.

Dispositivo	Costo [US $]	Dimensiones [mm]	Características	Observaciones
ESP Wroom 32 (WeMos).	US $23	91 x 30 x 20	WiFi, autonomía, bajo costo, conexión de batería incluida.	Tamaño demasiado grande.
ESP32 Lolin32.	US $15	25 x 40 x 8	WiFi, conexión de batería para funcionamiento autónomo, menor costo.	No posee divisor de voltaje incluido.
Adafruit QT Py ESP32-S3/ S2 WiFi Dev Board with STEMMA QT.	US $14	21,7 x 17,8 x 5,7	WiFi, tamaño compacto, compatibilidad con módulo de carga.	Tamaño reducido, buena autonomía.

In an initial phase, we started with a WeMos brand Wroom32 ESP (Figure 3 a) with an included 18650 battery module, which met the qualities of WiFi, autonomy and low cost (US$23 without battery), but its dimensions are too large (91 mm x 30 mm x 20 mm). Later, we opted for an ESP32 Lolin32 (Figure 3 b), which also meets the qualities of WiFi, battery connection for autonomous operation, lower cost (US$15 without battery) and a size of 25 mm x 40 mm x 8 mm. However, this did not have a voltage divider built into the circuit required to measure the battery voltage.

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Figure 3 Different ESP32 models.

Finally, the "Adafruit QT Py ESP32-S3 WiFi Dev Board with STEMMA QT" and "Adafruit QT Py ESP32-S2 WiFi Dev Board with STEMMA QT" models were chosen due to their WiFi connectivity, compact size of 21.7 mm x 17.8 mm x 5.7 mm, and compatibility with a charging module that does not significantly increase its size, the "Adafruit LiIon or LiPoly Charger BFF Add-On for QT Py". with a cost of US$14 and US$5 respectively without battery. These microcontrollers also have the ability to enter a low power "deep sleep" mode with a minimum consumption of 70 uA [11] .

By choosing two compatible components from the same brand, the battery charger module is connected as a shield to the same pins of the device, with a voltage divider connected to pin A2 to measure the battery level (Figure 3 c).

Another important aspect of the hardware is the packaging of the circuit within a protective casing. For this purpose, Autodesk Fusion 360 software (Figure 4 a) was used for 3D digital modeling. The casing was then 3D printed using PLA on a Creality K1 Max printer (Figure 4 b), creating a robust and functional physical model for use in a real-life context.

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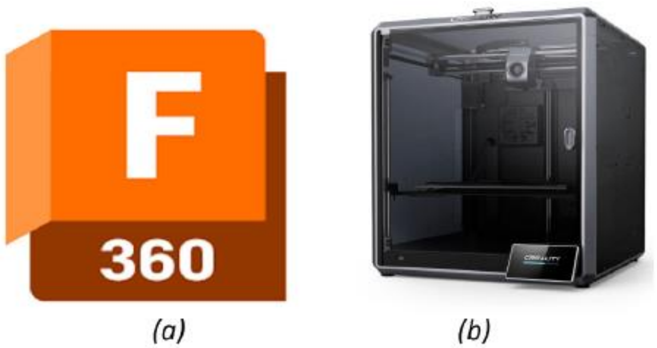

Figure 4 Tools used for circuit packaging.

Firmware Development (Microcontroller)

The development of the firmware required for the ESP32 microcontroller was done in C++ using the Arduino development environment. To achieve this, several essential libraries were used, including WiFi.h and HTTPClient.h. The WiFi.h library provides the functions necessary for connecting to WiFi networks, while HTTPClient.h allows for making HTTP requests, which are necessary for sending data to the web server.

This firmware allows the ESP32 to connect to a Wi-Fi network, scan for available networks, and send this data to a web server, entering deep sleep mode to save power between each data transmission cycle.

For a better understanding of the firmware, a flowchart is presented in Figure 5. The process begins with the connection to the WiFi network and a 10-second timer is started. If the device fails to connect to the network within that time, it enters deep sleep mode to save battery. If the device connects to the network before the 10 seconds are up, it continues with the normal flow, scanning all nearby networks. The collected data is organized in an array where the MAC of the

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transmitting WiFi TAG itself, its battery level, and the SSID, MAC, and RSSI of all found networks are recorded, and then sent to the server via a GET request. Subsequently, the device enters deep sleep mode for a defined time, repeating this cycle until the battery runs out.

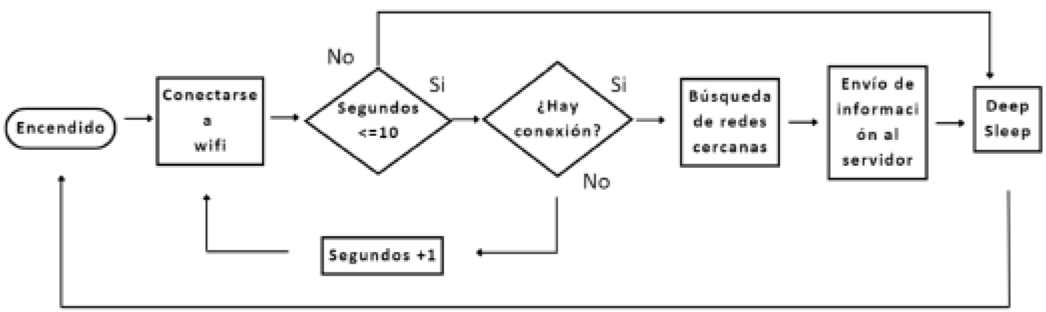

Figure 5 WiFi TAG firmware flowchart.

Battery optimization

Since one of the project's objectives is to develop a low-power model to optimize the battery and maximize its duration on a single charge, a plan was designed to measure the device's energy consumption using the Joule Scope [12] instrument , which measures current consumption as a function of time. This measurement was performed by connecting the device's power source (battery) to the -IN and +IN terminals, and the -OUT and +OUT terminals to the WiFi TAG's battery connector (Figure 6 a), and then directly connecting the measuring device to the computer with the Joule Scope application running.

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Figure 6 Measurements with Joule Scope (12) on ESP32 S2 and S3 data transmission.

After optimizing the code to reduce WiFi connection and data transmission times, it was decided to optimize the power-up, transmission, and deep sleep entry frequencies based on measurements obtained with the Joule Scope for each scan and transmission cycle. Here, we analyzed the behavior of a WiFi TAG in network connection, transmission, and deep sleep modes, and then analyzed the power consumption and time by observing the area under the curve for each phase (Figure 6 b).

From the measurements taken, various parameters related to the device's energy consumption were obtained, such as the charge consumed during data transmission and the charge consumed in deep sleep mode, both measured in coulombs.

Additionally, the data transmission time was recorded, and the deep sleep time configured in the firmware was verified, both measured in seconds. With this information, equation (1) was established to then calculate the optimal deep sleep time, based on the expected final duration (T_f) of the WiFi TAG.

According to the nomenclature expressed in Figure 7 , from a proportionality rule, the average current I_{prom} is obtained , which is consumed in each transmission-hibernation cycle, as expressed in equation (1):

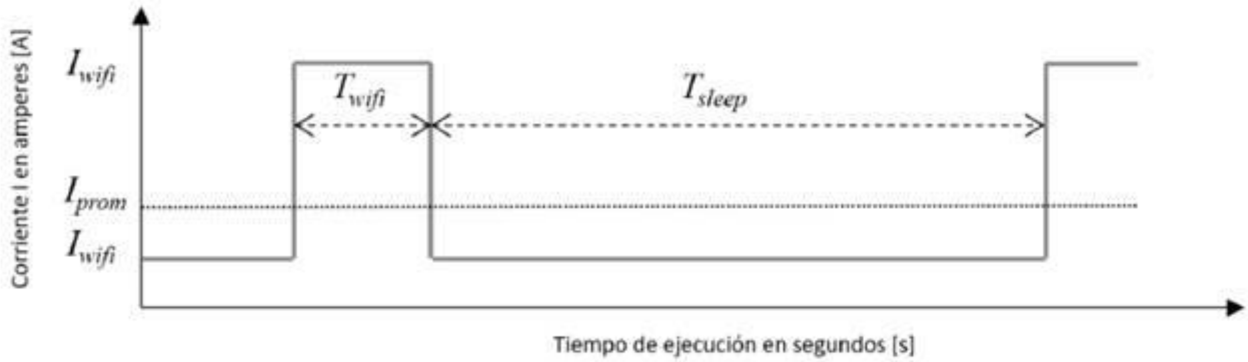

Figure 7 Current consumption cycle diagram according to execution time.

$$I_{prom} = \frac{I_{wifi}T_{wifi} + I_{sleep}T_{sleep}}{T_{wifi} + T_{sleep}} \quad (1)$$

Considering a known charge of the battery C_{bat} normally expressed in milliamps per unit of time, its duration can be estimated by dividing by the average current consumption I_{avg} of each cycle. In this way the estimated final duration time T_f can be determined according to equation (2):

$$T_f = \frac{C_{bat}}{\left(I_{wifi} \cdot T_{wifi} + I_{sleep} \cdot T_{sleep}\right)} \cdot \left(T_{wifi} + T_{sleep}\right) \quad (2)$$

Where,

- Tf=Expected duration time in seconds [s].
- Twifi = Transmission time in seconds [s].
- Tsleep = Microcontroller hibernation time in seconds [s].
- Cbat = Battery charge in milliampere seconds [mA/s].

• Iwifi = Current consumed in transmission in milliamperes [mA].

• Isleep = Current consumed during hibernation in milliamperes [mA].

Finally, under a simple algebraic development, a general formula is obtained to estimate the optimal time T_{sleep} based on the expected final duration time Tf, given the regular transmission time T_{wifi} as represented in equation (3):

$$T_{sleep} = \frac{C_{bat} \cdot T_{wifi} - T_f \cdot I_{wifi} \cdot T_{wifi}}{T_f \cdot I_{sleep} - C_{bat}} \quad (3)$$

Web application

The web application is structured on a standard Linux server running the https://www.sigem-uv.cl domain. Server programming is based on PHP, JavaScript, HTML, and CSS. The programming logic is implemented with PHP, animations and data updates with JavaScript, the web page structure with HTML, and styling with CSS and Bootstrap for usability.

TAG data processing

As is already known, there is an interaction between the WiFi TAG firmware and the web server as shown in Figure 1. It is necessary to explain how the server interacts with the information provided by the TAG. Within the SIGEM-UV server, there is a module dedicated to active location. Here, there is a PHP code in charge of collecting all the GET requests made by the TAG, adding the date and time of transmission and saving them in a CSV file to then be analyzed by the server (Figure 8).

Figure 8 Representation of WiFi TAG data processing.

Interaction between codes

For a better illustration of how the web application code and its user interface work, the diagram in Figure 9 has been created . This diagram shows the interaction between the different components of the code, where three main actions can be distinguished: the initial loading of the interface, then the loading of available devices, and then the selection of devices.

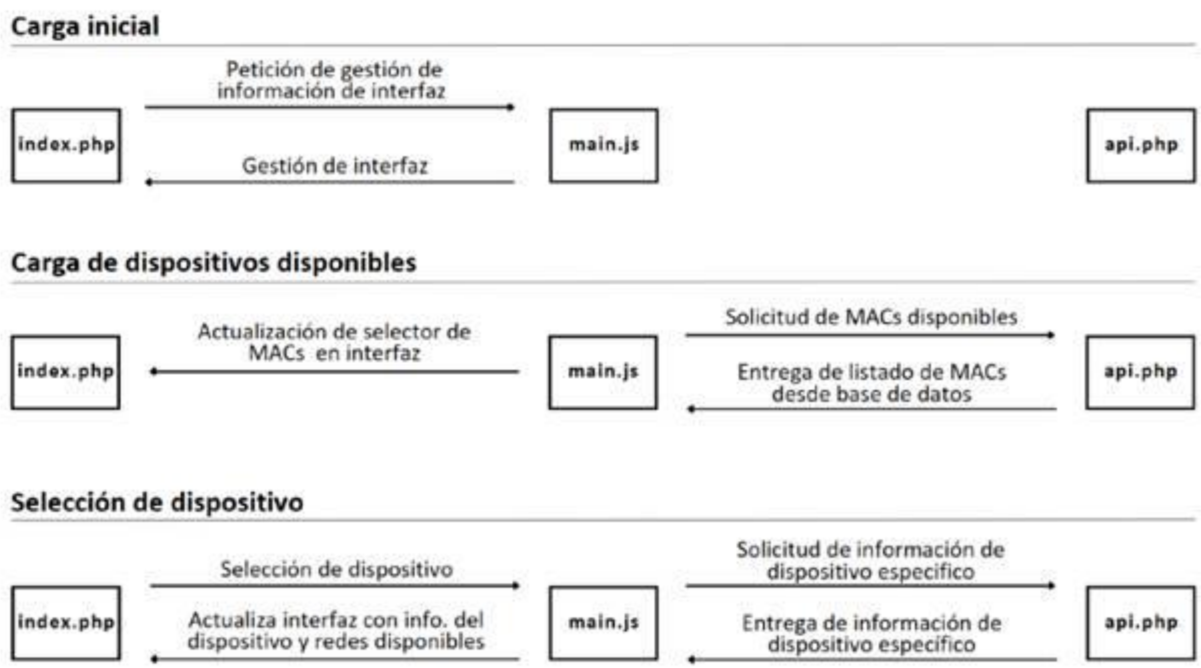

Figure 9 Interactions between PHP and JS codes.

- Initial Load: In the first stage, when the user accesses the module's web page, the index.php file is loaded. This file makes the request to manage information from the interface by calling the main.js file, which is responsible for managing the user interface, configuring the necessary elements for the system to function correctly. This stage prepares the visual and functional environment for user interaction.

- Loading available devices: Once the interface is configured, main.js sends a request to api.php to retrieve the list of MAC addresses of the WiFi tags associated with the available devices. api.php processes this request by interacting with the MySQL database, from which it extracts information about the available MAC addresses and devices. After obtaining the information, api.php returns it to main.js, which updates the device selector in the user interface, allowing the user to view and select from the available MAC addresses.

- Device Selection: When the user selects a device from the drop-down menu, main.js sends a request to api.php requesting specific information about the selected device. api.php processes this request by extracting the relevant information from the database. During this process, the last transmission from the selected device is analyzed, specifically filtering by the network used. All detected WiFi networks are then sorted from highest to lowest received signal strength, and the MAC addresses of the available access points in the database are compared, as seen in the bottom left of Figure 10 .

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Figure 10 User interface for device location.

Using a simple analysis, the floor the device is on is determined based on the best RSSI signal match between the last transmission and the data in the database. api.php then sends this information back to main.js. Once main.js receives the data, it updates the UI to display information about the selected device, including the Wi-Fi networks detected in the area, the floor it's on, the date and time of the last transmission, and the battery level.

RSSI Measurement

For this analysis, a survey of RSSI signals was carried out in the hallways of three floors of the Faculty of Engineering of the University of Valparaíso (6-story campus of approximately 9,000 m ^{2}), with the objective of visualizing the "WiFi illumination" of each floor and understanding the relationship and interference of the networks from one floor to the next. An experiment was designed to take

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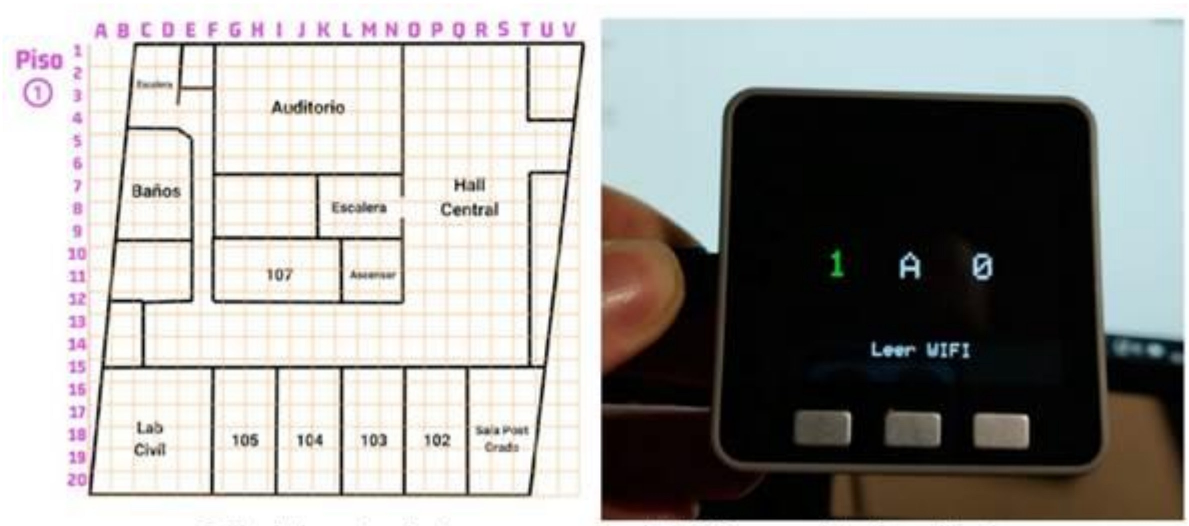
samples of RSSI signals every 4 square meters, creating a "checkerboard" pattern (Figure 11 a) on each floor, with columns labeled from the letter A to V and rows numbered from 1 to 20. To carry out this survey, a schematic plan of the building was used and a special program was developed for the M5 Core device, which includes an interface that allows the floor and the alphanumeric coordinate of the position to be selected, and then read all the WiFi networks at that location (Figure 11 b) and send them to the server to be saved in a CSV file. This procedure was applied in all accessible hallways and rooms on floors 1, 2 and 3.



a. Grilla de levantamiento. b. M5 Core con interfaz utilizada.

Figure 11 Example of grid and device used for RSSI survey.

RESULTS AND DISCUSSION

Hardware

El hardware seleccionado es un "Adafruit QT Py ESP32-S2 WiFi Dev Board with STEMMA QT" y un "Adafruit LiIon or LiPoly Charger BFF Add-On for QT Py".

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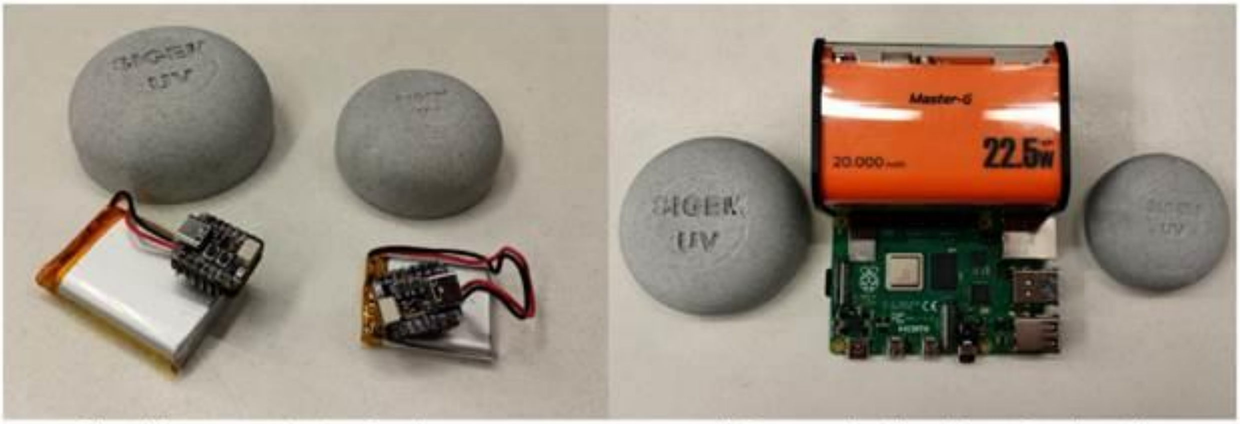
With the device selected, the ESP32 was connected to its charging module as shown in Figure 12 .

Figure 12 Final device circuit.

Once the ESP32 was integrated with its charging module, it was used with 2,000 mAh and 500 mAh batteries. Due to the need to accommodate two different battery sizes, two types of cases were designed, as shown in Figure 13 a. The final dimensions of the cases were 70 x 70 x 28.5 mm for the device with the 2,000 mAh battery and 55 x 55 x 25 mm for the device with the 500 mAh battery. These cases represent a volumetric reduction of 59.4% and 78% respectively, compared to the Raspberry Pi 3 plus battery (85 x 56 x 72 mm) used in an earlier version of the project (Figure 13 b).



a. Dispositivos en sus dos tamaños de carcasas b. Comparación dispositivos y Raspberry Pi

Figure 13 End devices and size comparison.

Battery optimization

By applying equation (3), it was possible to parameterize the deep sleep time using the data provided by the Joule Scope for each of the variables. The results obtained are presented in Table 2 and Table 3 , which show the deep sleep time in seconds, minutes, hours or times per day, depending on the number of months the device is expected to operate on a single charge, and given the size of the battery used.

Table 2 Tsleep results for 500 [mAh] battery.

Table 3 Tsleep results for 2,000 [mAh] battery.

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Tiempo entre ciclo de transmisión				
Meses de transmisión	Segundos	Minutos	Horas	Veces x día
1	593,3	9,9	0,2	145
2	1207,0	20,1	0,3	72
3	1820,8	30,3	0,5	48
4	2434,6	40,6	0,7	36
5	3048,3	50,8	0,8	28
6	3662,1	61,0	1,0	24
7	4275,9	71,3	1,2	20
8	4889,6	81,5	1,4	18
9	5503,4	91,7	1,5	16
10	6117,2	102,0	1,7	14
11	6730,9	112,2	1,9	13
12	7344,7	122,4	2,0	12

Considering that in the national hospital context, the accreditation regulations for facilities establish the need to implement maintenance (annual or semi-annual) for critical or relevant medical equipment [13] , a scenario is established for the use of the WiFi TAG in periods of 6 months for more critical equipment or 12 months for medical equipment with annual preventive maintenance. During this preventive maintenance process, it is possible to incorporate the replacement or recharging of the WiFi TAG battery. Based on the above, Table 2 highlights the estimate of T_{sleep} for a duration of 6 months and Table 3 highlights the estimate for a duration of 12 months.

Under this analysis, the optimal T sleep time for the 500 mAh device was determined to be approximately 20,450 seconds, equivalent to four transmissions per day, enabling a battery life of six months. For the 2,000 mAh device, the optimal T_{sleep} time is

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approximately 7,345 seconds, equivalent to twelve transmissions per day, ensuring a battery life of 12 months.

Although it is possible to extend battery life by using higher-capacity batteries, this increases both the device's cost and size. Similarly, choosing a very small battery to minimize device size requires increasing deep sleep times, reaching a point where it becomes impractical to have a tag that transmits only every few days instead of several times a day.

RSSI Measurement

As previously indicated, to determine the WiFi signal strength levels received, the data recorded during the survey were analyzed. The information was coded according to the schematic drawings presented in Figure 14 , where each measurement point was coded based on the floor and coordinates.

Figure 14 Schematic plans of the 3 floors considered in the survey.

The measurement results were stored in a database, from which a pivot table was extracted (Figure 15), and the results were analyzed using the Tableau Public application. The amount of data considered in the study exceeds 38,000 records. It is important to highlight that the search process for available networks detects all networks present in the premises, including mobile devices and computers in

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access point mode. For this reason, the developed system allows filtering only those SSIDs/MACs that are known, that is, those whose location is fixed on the schematic plans according to a previous survey.

DateTime	Piso	X	Y	SSID	MAC	RSSI
22-07-2024 10:32	1	A	2	TV UV	C4:72:95:80:DE:66	-56
22-07-2024 10:32	1	A	2	eduroam	C4:72:95:80:DE:63	-56
22-07-2024 10:32	1	A	2	Visitas UV	C4:72:95:80:DE:65	-56
22-07-2024 10:32	1	A	2	Fablab	C4:72:95:80:DE:64	-57
22-07-2024 10:32	1	A	2	Fun./Acad. UV	C4:72:95:80:DE:61	-57
22-07-2024 10:32	1	A	2	Alumnos UV	C4:72:95:80:DE:60	-57
22-07-2024 10:32	1	A	2	Acreditación	C4:72:95:80:DE:68	-57
22-07-2024 10:32	1	A	2	TV UV	00:AF:1F:B6:32:66	-62
22-07-2024 10:32	1	A	2	Visitas UV	00:AF:1F:B6:32:65	-62
22-07-2024 10:32	1	A	2	Acreditación	00:AF:1F:B6:32:68	-63
22-07-2024 10:32	1	A	2	Fablab	00:AF:1F:B6:32:64	-63
22-07-2024 10:32	1	A	2	Fun./Acad. UV	00:AF:1F:B6:32:61	-63
22-07-2024 10:32	1	A	2	eduroam	00:AF:1F:B6:32:63	-63
22-07-2024 10:32	1	A	2	Alumnos UV	00:AF:1F:B6:32:60	-63
22-07-2024 10:32	1	A	2	Alumnos UV	08:96:AD:B7:C6:10	-64
22-07-2024 10:32	1	A	2	Acreditación	08:96:AD:B7:C6:18	-64
22-07-2024 10:32	1	A	2	Fablab	08:96:AD:B7:C6:14	-64
22-07-2024 10:32	1	A	2	TV UV	08:96:AD:B7:C6:16	-64
22-07-2024 10:32	1	A	2	Fun./Acad. UV	08:96:AD:B7:C6:11	-64

Figure 15 Extract of pivot table with RSSI survey result.

This obtained the signal strength (RSSI) for each AP at all coordinates of the data collection. Just as an example, the graphical result of the signal strength detected by the device for two APs located on the second floor of the facility is presented. As can be seen in the upper part of Figure 16 , the AP located in the room 210 sector "illuminates" the nearby sector with greater signal strength. A similar pattern is shown in the lower part of Figure 16 for the AP located in the room 203 sector. Consequently, the radial decrease in strength as a function of distance is empirically confirmed.

Figure 16 Graphical result of RSSI measurements of 2 selected access points on floor 2 and their effect on floors 1 and 3.

Considering that there are between 3 and 6 AP devices connected to the main network on each floor of the facility, the minimum information required for the trilateration algorithms to estimate the position of the TAG device is available.

It is important to highlight that estimating the position of the devices for the defined context of use (large hospitals) does not require high precision. In other words, the objective of the implemented system is met if the floor and approximate sector where the TAG, and therefore the medical equipment in question, are located can be located.

Limitations and technical considerations

Although the results obtained with the WiFi TAG system have been positive in terms of locating medical equipment in controlled environments, it is crucial to consider several limitations and technical aspects that could affect its implementation in real-world hospital settings.

One of the main challenges is the areas of a hospital where medical equipment such as MRIs and CT scanners generate strong electromagnetic fields. This can interfere with the Wi-Fi system's radio frequency signals, affecting the location of the equipment in some areas of the facility. Previous studies on location in medical environments have highlighted this problem .

Furthermore, interference in hospital areas where multiple wireless communication systems coexist, coupled with the operation of electromedical devices, can degrade the quality of the WiFi signal and, consequently, the accuracy of the WiFi TAG system. Previous research exploring technologies such as Zigbee and sensor networks in these environments has shown that such interference can make device localization difficult, especially when multiple systems are operating simultaneously [6] .

Another crucial aspect is the dependence on adequate Wi-Fi coverage within the hospital. The effectiveness of the TAG Wi-Fi system directly depends on the availability of well-distributed access points and a stable signal in the different areas of the hospital. In areas with poor coverage, such as those with shadows or physical obstructions, location errors or even signal loss may occur. Research has shown that variability in Wi-Fi coverage in large buildings is a significant limitation that can impact the system's accuracy and reliability [8] . However, this dependence of the system on the hospital's Wi-Fi network, while a limitation or essential requirement, also represents the main advantage of the developed system, which does not require the installation of a new technological infrastructure, which would be highly complex and expensive to implement in operating hospitals.

To mitigate some of these problems, implementing dedicated VLANs exclusively for medical equipment could isolate network traffic from WiFi TAG devices, avoiding potential interference or saturation that could affect their performance. This approach has been suggested in other studies as an effective way to ensure the security and proper functioning of location systems in hospitals [9] .

Finally, security considerations are fundamental in any information system. However, it is important to highlight that the proposed system does not interact with medical equipment or patient-related information. Consequently, the developed system does not access sensitive information, as its purpose is solely to support the location and management of these devices by hospital technical staff.

Conclusions

The development and implementation of the active location system for medical equipment based on WiFi TAG technology has proven to be a viable, efficient, and low-cost solution. The device's design has been significantly optimized compared to its previous version, achieving a hardware size reduction of 59.4% and 78%, thanks to the use of the "Adafruit QT Py ESP32-S2 WiFi Dev Board" microcontroller in conjunction with the "Adafruit LiIon or LiPoly Charger BFF Add-On for QT Py". This advancement allowed for the design of more compact housings, suitable for 2000 mAh and 500 mAh batteries, maintaining the autonomy and functionality necessary for hospital environments without compromising portability.

A highlight of the project is the optimization of energy consumption. By implementing deep sleep cycles and efficient energy management, the device's battery life was significantly extended. Estimates using 500 mAh batteries project a battery life of up to 6 months, while 2000 mAh batteries would allow the device to operate continuously for up to 12 months on a single charge. This balance between transmission frequency and energy consumption ensures a practical and sustainable solution for the continuous location of medical equipment in hospitals.

Despite the positive results, it is important to consider the limitations that may arise in real-life hospital settings. One of these is the potential lack of Wi-Fi network coverage in some areas of the facility or the existence of areas with increased interference, which could limit the system's accuracy. This could be offset by better distributing Wi-Fi access points to ensure consistent coverage and proper location in different areas of the hospital.

In conclusion, the WiFi TAG system represents an efficient, low-cost solution with reasonable battery life. The considered usage scenarios were adjusted to achieve TAG battery life of up to 6 months with 500 mAh batteries and up to 12 months with 2000 mAh batteries, which coincides with the regular maintenance cycles of relevant medical equipment. These features, along with the significant reduction in device size, make it suitable for locating medical equipment. However, for its successful implementation, extensive testing in real-world hospital environments is necessary, as well as addressing any limitations related to WiFi coverage.

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