Integrated IoT System for Remote Health Monitoring in Home Hospitalization

Sergio Gramajo
CInATIC *(Centro de Investigación Aplicada en TICs)*
Universidad Tecnologica Nacional
Resistencia, Argentina
sergiogramajo@gfe.frre.utn.edu.ar

Carlos Torres
CInATIC *(Centro de Investigación Aplicada en TICs)*
Universidad Tecnologica Nacional
Resistencia, Argentina
carlos.ing.2013@gmail.com

Salvador Nuñez
CInATIC *(Centro de Investigación Aplicada en TICs)*
Universidad Tecnologica Nacional
Resistencia, Argentina
salvador.nunez@gfe.frre.utn.edu.ar

Reinaldo Scappini
CInATIC *(Centro de Investigación Aplicada en TICs)*
Universidad Tecnologica Nacional
Resistencia, Argentina
rscappini@gfe.frre.utn.edu.ar

Jorge Roa
CInATIC *(Centro de Investigación Aplicada en TICs)*
Universidad Tecnologica Nacional
Resistencia, Argentina
roajorge@gfe.frre.utn.edu.ar

Raul Montiel
CInATIC *(Centro de Investigación Aplicada en TICs)*
Universidad Tecnologica Nacional
Resistencia, Argentina
raulmontiel@gfe.frre.utn.edu.ar

***Abstract*—The COVID-19 pandemic underscored the critical need for scalable and scientifically validated remote health monitoring systems. This work presents the development of an IoT system designed to monitor physiological and environmental parameters in home-hospitalized patients. The architecture comprises two complementary prototypes: (1) a wearable device capturing cutaneous temperature, single-lead ECG, pulse oximetry (SpO_2), non-invasive blood pressure monitoring, and fall detection; and (2) an environmental sensor unit recording atmospheric pressure, ambient temperature, light intensity, relative humidity, and CO_2 levels. Data is transmitted via hybrid WiFi/LoRaWAN connectivity to a cloud-based server utilizing optimized MQTT/CoAP protocols, where data science, through machine learning algorithms, generates real-time clinical alerts. Preliminary results demonstrate successful validation of the system architecture, rigorous medical sensor selection (AD8232, MAX30102), and proof-of-concept deployment. The solution shows significant potential to reduce the burden on hospital resources and enhance emergency response effectiveness in home-based care scenarios.**

***Keywords*—Telemedicine; Medical IoT (IoMT); Remote Patient Monitoring; Health Data Analytics; e-Health.**

I. Introduction

The Internet of Things (IoT) has emerged as a disruptive technology that is fundamentally redefining the interaction between people and information systems globally [1]. In the healthcare sector, this pervasive interconnection has given rise to the Internet of Medical Things (IoMT), a vast network of internet-connected medical devices, sensors, applications, and health systems capable of generating, analyzing, and transmitting real-time health data [2]. The implementation of IoMT is crucial for addressing growing challenges in healthcare, such as the rise in chronic diseases and an aging population, facilitating more proactive and personalized health management. Accelerated by the COVID-19 pandemic, IoMT has played a vital role in ensuring continuity of medical care and has driven an unprecedented digital transformation in the sector [3].

Among the key benefits and significant advancements offered by IoMT in medical care are the real-time monitoring of vital signs like heart rate, blood pressure, glucose, and oxygen levels, enabling healthcare professionals to respond immediately to emergencies such as asthma attacks, heart failure, or critically low blood sugar. Furthermore, it facilitates remote patient care and telemedicine, significantly reducing the need for in-person visits and supporting continuous patient observation for accelerated recovery and prevention of readmissions, which is particularly vital for patients in rural areas with limited access to healthcare centers [4], [5]. IoMT also leads to improved diagnosis and treatment by providing comprehensive and accurate data, allowing for early detection of anomalies, more precise diagnoses, and personalized adjustment of treatment plans. These advancements collectively contribute to reduced operational costs through remote monitoring, process automation, and personalized treatments, minimizing visits, hospitalizations, and human errors. Finally, IoMT fosters greater patient engagement by providing real-time access to health information and continuous feedback, empowering individuals to proactively participate in their health management, and generates vast amounts of data crucial for medical research and the development of new treatments and predictive models [6].

The functionality of IoMT relies on enabling technologies and innovative algorithms (Artificial Intelligence (AI) and Machine Learning (ML), which include multiparametric sensors capable of monitoring various physiological parameters, and diverse connectivity options such as Wi-Fi, Bluetooth, LoRa, and 5G [7].

Despite these promising advances, the expansion of IoMT introduces significant challenges that must be meticulously addressed for its secure and effective implementation. Paramount among these are data security and patient privacy, given the highly sensitive nature of health information and its cybersecurity [8].

Nevertheless, the future of IoMT is exceptionally promising, with projections of exponential growth in connected devices within hospitals and homes alike. Anticipated developments include a deeper integration of AI for increasingly autonomous and proactive monitoring capabilities, coupled with the widespread deployment of 5G technology for faster and more reliable data transmission.

Edge computing is also set to gain further prominence, enabling real-time data processing and reduced latency by bringing computation closer to the data source [9]. These ongoing advancements are poised not only to enhance patients' quality of life but also to pave the way for more sophisticated treatments and a more accessible and efficient global healthcare system [9] [10]

II. Proposed IoT Architecture

This project employs a well-established, three-layer IoT architecture to ensure a robust and scalable system for patient monitoring. This model, consisting of the Perception, Network, and Application layers, provides a clear and organized framework for data flow, from initial collection at the device level to final analysis and application in the cloud. See Fig. 1.

Perception Layer: This foundational layer is the physical interface of the system, responsible for sensing and collecting raw data from the patient and their environment. It is composed of various IoT hardware components, including microcontrollers and an array of sensors (e.g., heart rate monitors, temperature probes, and accelerometers). The primary functions of this layer are:

- Data Acquisition: It continuously collects a wide range of physiological and environmental data.
- Analog-to-Digital Conversion (ADC): Raw analog signals from the sensors are converted into a digital format that can be processed.
- Initial Data Pre-processing: To optimize data transmission, the perception layer performs basic, on-device operations. This includes filtering, possibly using edge ML, to remove noise and compression to reduce the data payload size. This pre-processing is crucial for minimizing bandwidth usage and energy consumption, particularly in battery-powered devices. Furthermore, the ability to process data locally using edge ML techniques reduces latency in the event of critical alerts.

Network Layer: Acting as the communication backbone, this layer is crucial for the secure and reliable transfer of data from the perception layer to the cloud. It manages all aspects of connectivity and routing. To ensure high availability and reliability for critical patient data, our system utilizes a dual-connectivity approach with both Wi-Fi and LoRa technologies.

- Wi-Fi: Used for high-speed, high-bandwidth data transmission when a network is available. It is ideal for sending larger data packets or for real-time monitoring from sensors.
- LoRa/Public GPRS/LTE: Provides a long-range, low-power alternative. This technology ensures that data can still be transmitted over a wide area, even in environments with poor or no Wi-Fi coverage. This redundancy is vital for mission-critical applications where a loss of connectivity could be life-threatening.
- Data Exchange Protocols: For communication, we employ MQTT (Message Queuing Telemetry Transport) an efficient protocol that minimizes bandwidth and power consumption, making it an excellent choice for resource-constrained devices.

Application Layer: The top layer of the architecture is where all the value is created from the raw data. It serves as the intelligent core of the system, handling data storage, processing, and analysis. This layer is typically cloud-based and includes services for:

- Data Storage: Secure databases are used to store both real-time and historical patient data. The system is designed to comply with data privacy to ensure data security and confidentiality.
- Processing and Analytics: algorithms and machine learning models are applied to the data to derive meaningful insights.
- User Interface (UI): This layer also includes the front-end application (e.g., a dashboard or mobile app) that allows doctors and caregivers to visualize data, receive notifications, and interact with the system. The entire system is built to be adaptable to the specific requirements of different healthcare scenarios.

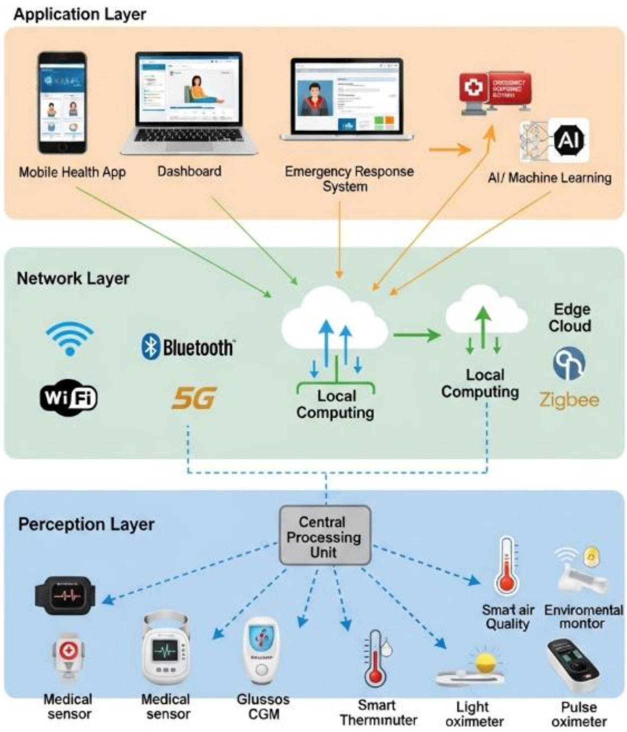

Fig. 1. Architecture

III. Modeled prototypes

The project, "Remote Monitoring: Development of Prototypes for Medical Services (Home and Ambulatory Hospitalization)," has made substantial progress towards our research. This initiative specifically addresses the critical need to integrate applications, data science algorithms, telecommunications, sensors, and systems to provide real-time remote healthcare support. A key focus has been to overcome the existing gap in studies and validated models necessary for the successful and scalable implementation of such solutions, ensuring academic rigor in their outcomes.

The main achievements in the prototypes development include:

- Dual-Focus Prototype Deployment: During 2023, the project initiated the development of two distinct prototypes. The first prototype is dedicated to analyzing and measuring medical variables of interest in labs, while the second focuses on monitoring the environmental conditions. Both prototypes are equipped with independent telecommunication systems designed to transmit collected data to a remote monitoring center for access by healthcare professionals.

- Initial sensor integration includes capabilities for skin temperature, oximetry, blood pressure, heart rate, ECG (Lead II), and fall detection via an accelerometer.

- Core design principles emphasize energy efficiency, ergonomic design, high system accuracy, robust data processing, reliable connectivity, adequate internal storage, and versatile operational modes (both online and offline).

The implemented system architecture follows a three-layered IoT model described above: the Perception Layer (handling hardware, sensor data acquisition, and initial pre-processing), the Network Layer (managing connectivity and data transfer, notably using MQTT protocol), and the Application Layer (responsible for data storage, advanced processing, and secure user access control).

To build this prototypes we use several electronic devices such as:

The central processing unit of the main device is an ESP32 chip, leveraged for its dual-core CPU, considerable memory, integrated Wi-Fi and Bluetooth modules, a Real-Time Clock (RTC), and a 12-bit Analog-to-Digital Converter (ADC), facilitating diverse operational modes.

The device's firmware is systematically organized into three stages:

1. Sensor Data Acquisition and Queuing.
2. Critical calculations (e.g., detecting falls, abnormal vital signs such as temperature, heart rate, blood pressure, and SpO2 levels).
3. Data Classification, distinguishing between critical events or routine transmissions.

Detailed functionalities include the ability to precisely interpret ECG signals across various derivations (I, II, III, aVR, aVL, aVF, V1-V6) and the implementation of an automated blood pressure measurement system utilizing an inflatable cuff, a pressure sensor (e.g., MPX5050), and an electrovalve (see Fig. 2).

We use only derivation II in our first prototype.

Ambiental sensors are more simple like temperature, humidity, CO2, etc.

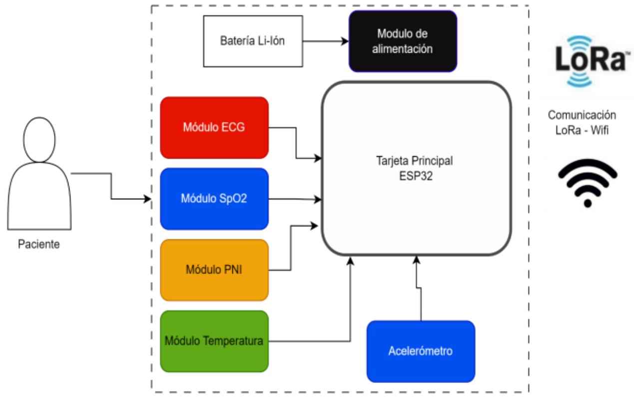

Fig. 2. Analyzed sensors

The IoMT provides key benefits and significant advancements in medical care.

These benefits are fundamentally driven by the real-time monitoring of vital signs, which include heart rate, blood pressure, and oxygen levels. This continuous monitoring capability is crucial for empowering healthcare professionals to respond immediately to emergencies such as critically low blood sugar, heart failure, or asthma attacks.

Additionally, IoMT greatly facilitates telemedicine and remote patient care. By supporting continuous patient observation, it significantly reduces the need for frequent in-person visits, thereby promoting accelerated recovery and the prevention of readmissions. This reduction in required physical visits is particularly vital for patients residing in remote areas who face limited access to traditional healthcare centers.

Finally, the availability of comprehensive and accurate data via IoMT leads to improved diagnosis and treatment outcomes. This data stream enables the early detection of anomalies, supports the formation of more precise diagnoses, and allows for the personalized adjustment of treatment plans. (see Fig. 3).

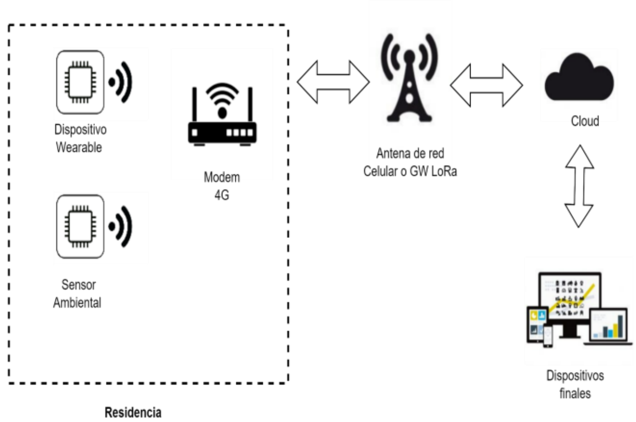

Fig. 3. Prototypes functionality

Once the final values for the environmental variables to be measured have been determined, the third stage is responsible for evaluating whether these values constitute an event or merely a temporary transmission. Temporary transmissions are those that are sent at a specific, predetermined time interval.

Once the data has been acquired and is available on the server, the final stage illustrates the interaction of the services with the end-user devices (see. Fig. 4).

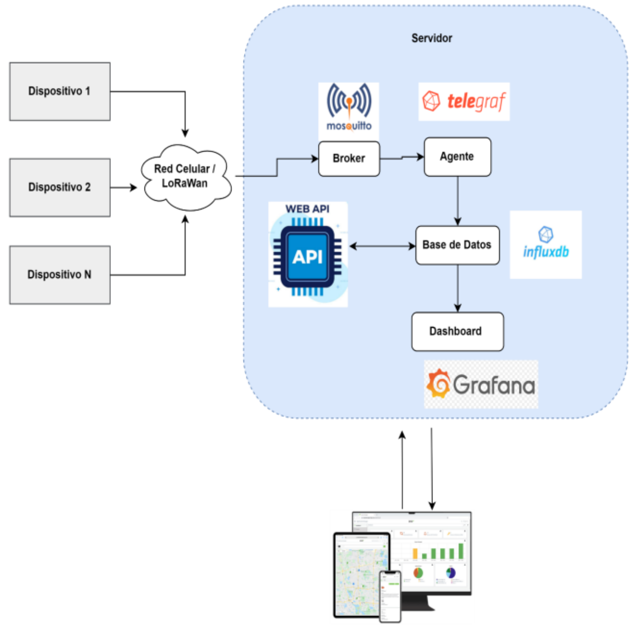

Fig. 4. System Workflow

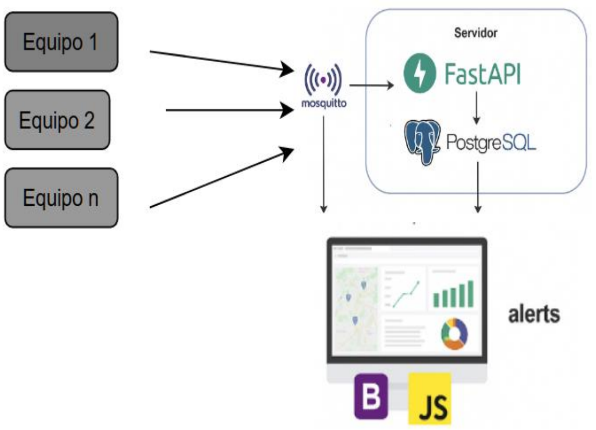

Fig. 5. Remote sensors interactions

IV. System workflow and operation

He we briefly explain operational workflow of the proposed remote health monitoring system. It is designed for reliability, autonomy, and timely intervention. The process, shown in Fig. 5, has these operational phases:

1. Data Acquisition and Preprocessing:

The wearable device, operating primarily in active mode, and the environmental sensor, operating primarily in deep sleep mode, simultaneously acquire raw physiological and environmental data. The ESP32 microcontroller performs immediate Analog to Digital Conversion (ADC). Initial ondevice preprocessing is then applied, including basic filtering (e.g., for noise reduction on the ECG signal) and data compression. This step optimizes the load for transmission, conserving bandwidth and energy.

2. Local Data Processing and Event Detection:

The preprocessed data is handled by the device's firmware or the cloud app, which executes critical calculations. For the wearable device, this includes:

Fall Detection: Analyzing accelerometer (MPU6050) data patterns to identify sudden impacts or abnormal orientation.

Vital Sign Analysis: Calculating heart rate from the ECG (AD8232) and SpO_2 from the oximeter (MAX30102), and determining systolic and diastolic pressure using the oscillometric method.

The results are compared against predefined clinical thresholds (e.g., $SpO_2 < 94\%$, heart rate outside safe bounds). If a threshold is breached, the data is immediately flagged as a critical event.

3. Data Transmission:

The system employs a hybrid connectivity strategy (WiFi, LoRaWAN, 4G) managed by the Network Layer. All data, whether routine or critical, is packaged for transmission using the lightweight MQTT protocol. Data is transmitted directly to the cloud based MQTT broker. This is the preferred method for its high bandwidth and low latency.

4. CloudBased Processing and Storage:

Upon receipt by the cloud broker, data is routed to the Application Layer. All data is stored in a secure database for each record of patients.

If an event is confirmed (either from the device's initial flag or the cloud's ML analysis), the system triggers realtime alerts. These alerts are pushed to designated endpoints via the Web API. See Fig. 6, 7 and 8.

Fig. 6. General View of remote patients

A centralized dashboard provides a comprehensive, realtime view of all patient data, including trends for vital signs and environmental conditions. It visually highlights any ongoing alerts

Fig. 7. Alert visualized

Fig. 8. Realtime info of patients

V. Conclusions and Future Work

The implementation of this integrated IoT and data science monitoring system has great potential to improve remote healthcare, providing timely information and facilitating real-time decision-making, even with the assistance of individuals without specialized medical training. The combination of physiological and environmental monitoring offers a comprehensive view of the patient's well-being.

Our work so far is promising; however, it is currently in the model validation stage.

Future work will focus on a more detailed validation of each of the characteristic ECG waves (beyond QRS and T), especially the ST segment, for a deeper pathological analysis. We will continue with the implementation of these algorithms in embedded systems for use in portable cardiac monitoring devices, and the exhaustive validation of data science models, potentially incorporating Convolutional Neural Networks for advanced arrhythmia classification.

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