

# POLITECNICO DI TORINO

Master's Degree in ELECTRONICS  
ENGINEERING COURSE



Master's Degree Thesis

## Development of a synchronous sensors' network's firmware

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## Abstract

The PRIMULA project seeks to address the key challenges in real-time monitoring and management of Parkinson's Disease (PD) symptoms through a wireless body area network (WBAN) framework. PD is characterized by debilitating motor symptoms, including bradykinesia, rigidity, and tremors, which necessitate accurate, continuous monitoring for effective treatment. Existing solutions face limitations in energy consumption, data synchronization, and real-time data transmission, especially in mobile and dynamic environments. The proposed system focuses on optimizing asynchronous communication, real-time data acquisition, and reliable data transmission, utilizing state-of-the-art protocols such as Network Time Protocol (NTP) and Message Queuing Telemetry Transport (MQTT).

The PRIMULA system's architecture integrates key components such as the Raspberry Pi Pico W microcontroller and Wi-Fi communication to ensure stable, long-range wireless communication. A modular design ensures scalability, allowing for future extensions with additional sensors. A circular buffer mechanism is employed to manage continuous data streams, preventing data loss during transmission, while asynchronous sensor nodes, synchronized via NTP, facilitate precise timekeeping critical for motion data analysis.

Firmware development is centered around improving energy efficiency and system reliability through optimized use of duty cycles and watchdog timers. The system was validated through a series of experiments focusing on synchronization accuracy, data transmission reliability, and overall system responsiveness. NTP synchronization achieved an average latency of 121.36 ms across 8,640 synchronization events, with a success rate of 99.44% on the first attempt. Data transmission via MQTT was verified with a 100% success rate over 6 hours, with transmission times averaging 1.43 ms. The PRIMULA system's performance was consistently reliable, demonstrating minimal latency in ADC data acquisition and data transmission under continuous monitoring conditions.

Future work will explore the integration of cloud-based processing for enhanced scalability, as well as hybrid communication protocols to further optimize power consumption and system performance. The results demonstrate that the PRIMULA framework provides a robust, real-time solution for the continuous monitoring of PD symptoms, positioning it as a critical tool for improving patient care and management.



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# Acronyms

## **5G NR**

5G New Radio

## **6LoWPAN**

IPv6 over Low-Power Wireless Personal Area Networks

## **ADC**

Analog-to-Digital Converter

## **AES**

Advanced Encryption Standard

## **AES-CCM**

Advanced Encryption Standard - Counter with CBC-MAC

## **AI**

Artificial Intelligence

## **AMQP**

Advanced Message Queuing Protocol

## **AODV**

Ad-hoc On-demand Distance Vector

## **AP**

Access Point

## **BAN**

Body Area Network

**BCC**

Body-Coupled Communication

**BLE**

Bluetooth Low Energy

**CH**

Cluster Head

**CMOS**

Complementary Metal-Oxide-Semiconductor

**CoAP**

Constrained Application Protocol

**CPU**

Central Processing Unit

**DDS**

Data Distribution Service

**DTLS**

Datagram Transport Layer Security

**eDRX**

extended Discontinuous Reception

**eMBB**

enhanced Mobile Broadband

**GATT**

Generic Attribute Profile

**GW**

Gateway

**HEED**

Hybrid Energy-Efficient Distributed Clustering

**IEEE**

Institute of Electrical and Electronics Engineers

**IMU**

Inertial Measurement Unit

**IoT**

Internet of Things

**IPsec**

Internet Protocol Security

**LAEEBA**

Link Aware and Energy Efficient Routing Protocol for WBAN

**LEACH**

Low-Energy Adaptive Clustering Hierarchy

**LED**

Light-Emitting Diode

**LoRaWAN**

Long Range Wide Area Network

**LPWAN**

Low Power Wide Area Network

**LTE-M**

Long Term Evolution for Machines

**MAC**

Medium Access Control

**MCU**

Microcontroller Unit

**MEMS**

Micro-Electro-Mechanical Systems

**mMTC**

massive Machine Type Communications

**MQTT**

Message Queuing Telemetry Transport

**NB-IoT**

Narrowband Internet of Things

**NIST**

National Institute of Standards and Technology

**NR**

New Radio

**OSI**

Open Systems Interconnection

**PD**

Parkinson's Disease

**PDR**

Packet Delivery Ratio

**PLR**

Packet Loss Rate

**QoS**

Quality of Service

**RSS**

Received Signal Strength

**SA**

Security Association

**SAR**

Specific Absorption Rate

**SDN**

Software-Defined Networking

**SIM**

Subscriber Identity Module

**TCP**

Transmission Control Protocol

**TLS**

Transport Layer Security

**UDP**

User Datagram Protocol

**URLLC**

Ultra-Reliable Low-Latency Communications

**WBAN**

Wireless Body Area Network

**Wi-Fi**

Wireless Fidelity

**WSN**

Wireless Sensor Network

# Chapter 1

## Introduction

In this chapter, the motivation and intention of this work will be described to provide a rough overview.

### 1.1 Background and Motivation

Wireless Sensor Networks (WSNs) and the Internet of Things (IoT) are rapidly transforming various aspects of our lives, including healthcare, industrial automation, agriculture, and environmental monitoring. In fact, the focus of this framework is on advancing the IoT-based health care system which has a significant effect on the lives of many people.

Postural instability, a difficulty maintaining balance, is a common symptom in various conditions like inner ear disorders, cerebrovascular diseases, and Parkinson's disease (PD). Due to technological advancements in smart healthcare, wearable devices offer significant advantages, including reducing patients' dependence on caregivers and lowering the costs associated with monitoring various biological parameters, particularly for elderly individuals [1, 2].

In the elderly, slowed reflexes and reduced muscle strength worsen the condition [3]. A standard wearable device consists of an IMU network that provides raw inertial data to measure common motor symptoms in PD, known as a perfect solution [4]. There are several different IoT-based wearable devices for PD, like WESAA [2], which offer a comprehensive analysis of the movement of patients. In this scenario, to effectively design a wearable device, a deep understanding of WSN architecture—which is a crucial part of this wireless device alongside application needs—should be considered.

Despite the immense potential, current WSN architectures designed and implemented in wearable devices face significant challenges due to the dynamic changes in the human body. Current WSN designs in healthcare movement monitoring

applications, known as Wireless Body Area Networks (WBAN), are often based on traditional IoT data communication protocols such as Open Systems Interconnection (OSI), which have limitations, including energy consumption [4].

This thesis builds upon the PRIMULA project, a collaboration with Brain Technology Company, which aimed to develop firmware for a conceptual prototype of a wearable device consisting of asynchronous sensors for assessing postural instability in PD patients. The firmware's role is to configure a single node to collect and transmit data from the inertial measurement unit (IMU).

## 1.2 Problem Statement

### 1.2.1 The PRIMULA Project and Asynchronous Communication for PD Monitoring

The PRIMULA project, a collaborative effort with Brain Technology Company, seeks to revolutionize the management of PD through wearable devices equipped with IMUs. These devices hold promise for enabling personalized treatment plans and accurately reconstructing body movements, which are crucial for understanding and managing PD symptoms. However, the dynamic nature of the human body poses significant challenges to the reliable operation of such devices. Variations in sensor performance and wireless signal quality, induced by body movements and environmental factors, can lead to increased energy consumption, higher latency, limited scalability, and reduced responsiveness [5, 4, 6].

To mitigate these challenges, PRIMULA employs asynchronous communication, a paradigm in which sensors operate independently and transmit data only when necessary. This approach significantly enhances energy efficiency across the network [7]. This is a critical factor for battery-powered wearables, while reducing interference in the crowded wireless spectrum of the human body [8, 9]. In fact, asynchronous communication also provides greater flexibility, allowing for the seamless addition or removal of sensors to accommodate the evolving needs of PD monitoring. Furthermore, it enables real-time responsiveness for the effective detection and management of PD symptoms [10].

This approach's implementation of asynchronous communication, utilizing the MQTT protocol and NTP time synchronization, underscores the feasibility and potential benefits in real-world PD monitoring scenarios. The system's efficacy is validated through testing, as detailed in Chapter 4, confirming its capability to accurately collect, synchronize, and transmit IMU data reliably.

### 1.2.2 Optimizing WBAN Performance: The Need for Advanced Routing and Data Aggregation

While our proposed approach in PRIMULA successfully demonstrates the advantages of asynchronous communication in a single-node WBAN, a comprehensive literature review reveals that optimizing routing and data aggregation is equally crucial for achieving scalable and efficient PD monitoring in real-world scenarios. Ensuring data accuracy and reliability is crucial for making informed diagnostic and treatment decisions [5, 3]. However, existing WBAN designs often struggle with maintaining packet-level synchronization accuracy across multiple nodes, which is essential for precise data analysis and correlation from multiple IMUs [11, 4, 12].

Real-time processing of sensor data from multiple nodes is another critical requirement for comprehensive PD symptom monitoring [3, 4]. The limited resources of wearable devices necessitate the development of reliable, scalable, and secure protocols for efficient data transmission and processing. Robust architectures are required to manage the growing volume of data generated by multiple sensors while maintaining real-time monitoring capabilities. This scalability introduces challenges such as precise synchronization among nodes, increased data transfer demands, and efficient energy management for data aggregation and processing [5].

## 1.3 Objective and Scope

This thesis aims to address the challenges identified in the problem statement by optimizing WSN design for real-time, cloud-based monitoring of PD in elderly patients. Central to this research is the evaluation of asynchronous communication within the PRIMULA project, focusing on its impact on energy efficiency, data transmission reliability, and real-time responsiveness. The study will identify potential limitations related to synchronization, data transfer demands, and energy management, and propose solutions based on insights from the literature review and PRIMULA project analysis.

## 1.4 Thesis Structure

This thesis is organized into five chapters, each addressing key aspects of the research question and contributing to the overall goal of developing an optimized firmware architecture for wearable PD monitoring devices.

- Chapter 2: Literature Review conducts a comprehensive analysis of existing WSNs and WBANs, identifying current challenges and gaps in PD monitoring technologies.

- Chapter 3: Conceptual Framework and System Design presents the architectural design of the PRIMULA system, detailing the integration of asynchronous communication protocols and the selection of suitable hardware components to enhance system efficiency and reliability.
- Chapter 4: Implementation describes the development and deployment of the PRIMULA prototype, including firmware development, system configuration, and rigorous testing procedures to validate the system's performance and functionality.

# Chapter 2

## Literature Review

### 2.1 Wireless Sensor Networks (WSNs) Technology

The standard architecture of a WSN comprises five fundamental components, with an additional one adjustable module tailored to specific applications (Figure ??) . These components are crucial for the operation and functionality of the WSN.

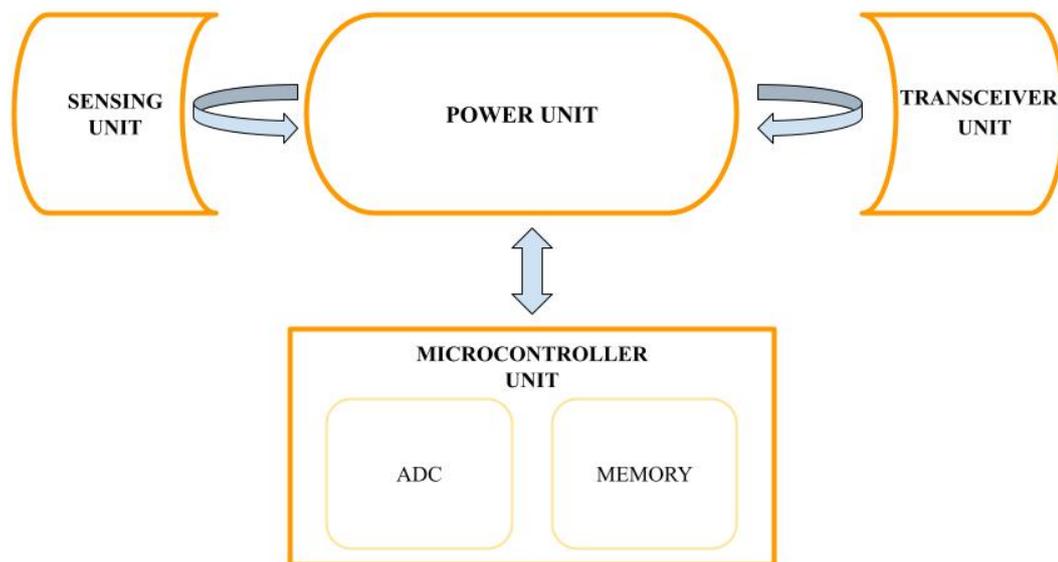


Figure 2.1: An example of the WSN architecture.

### 2.1.1 Power Unit

The power unit is the energy source for the WSN node, often relying on batteries due to deployment in remote locations. Battery lifetime is a critical design consideration, with energy harvesting techniques like solar or vibration offering potential solutions to extend operational life [13]. Power consumption is primarily attributed to sensing, communication, and data processing, with data transmission being particularly energy intensive. To mitigate this, duty cycling, where nodes alternate between active and sleep modes, can be employed [6]. Additionally, ambient energy harvesting (AEH) techniques, such as those using piezoelectric crystals or thermoelectric elements, can be utilized to power small sensor nodes [13].

### 2.1.2 Microcontroller Unit (MCU)

Acting as the "brain" of the WSN, the MCU controls all operations, including sensing, data processing, and communication. Low-power microcontrollers like the Texas Instruments MSP430 family are increasingly popular due to their energy efficiency and integrated peripherals [5]. The MCU also plays a crucial role in implementing network protocols like IEEE 802.15.4, essential for WSN communication. In IoT devices, the MCU often doubles as a portable processing device, with options like Arduino and ESP8266 offering flexibility and ease of use for various tasks [14]. The CPU of a sensor node is typically a microprocessor with flash memory, responsible for decision-making, data analysis, and communication with other nodes [15].

### 2.1.3 Memory

The memory module serves a dual purpose: storing sensed data and the device's programming. While the microcontroller often includes onboard memory, typically flash memory due to its cost-effectiveness and capacity, external memory options like SD cards or external flash memory chips may be necessary for data-intensive applications or firmware updates [16, 6]. Memory management techniques like data compression and aggregation are crucial for optimizing the use of limited memory resources.

### 2.1.4 Transceiver

This unit enables wireless communication between WSN nodes, transmitting data and receiving commands. The choice of wireless technology (e.g., Zigbee, Bluetooth Low Energy) impacts communication range, data rate, and power consumption. RF transceivers are the most common in WSNs, with typical ranges of 10 meters indoors and 100 meters outdoors. Design considerations for transceivers involve

trade-offs between data rate, range, power consumption, and cost, while also addressing challenges like interference and multi-path fading through techniques like channel hopping and diversity [6]. The transceiver operates in four states: receive, transmit, idle, and sleep.

### **2.1.5 Analog-to-Digital Converter (ADC)**

As most sensors generate analog signals, the ADC is crucial for converting these into digital data that the MCU can process. The ADC's resolution and sampling rate directly influence the accuracy and precision of the sensor data. In many WSN applications, the ADC is integrated into the microcontroller board for efficiency and compactness.

### **2.1.6 Sensor/Transducer Unit**

The sixth, adjustable module, the Sensor/Transducer Unit, is application-specific and comprises the sensors that interact with the environment to collect data. The choice of sensors depends on the WSN's purpose, ranging from temperature and humidity sensors for environmental monitoring to accelerometers for motion tracking and beyond. These sensors convert environmental variables into electrical impulses, with advancements in sensing technologies like MEMS, CMOS, and LED sensors expanding their capabilities and applications [5].

## **2.2 Communication Architecture for WSNs and OSI Model**

WSN uses a radio system which consists of two essential parts, a transmitter and a receiver. Both are necessary for nodes to communicate with each other in a network. The radio's role is to receive information from a central control system and relay it to other sensor nodes, as well as to receive data from other nodes and transmit it back to the central system. In a WSN, each sensor node sends its collected data to a parent node, which is connected to a central computer. This central computer acts as a hub, allowing users to access data from all nodes through a computer interface. Users can also send commands through the internet to the central computer, which then relays these commands to the parent node and subsequently to its child nodes [2].

The Open Systems Interconnection (OSI) model, a conceptual framework comprising seven distinct layers (Physical, Data Link, Network, Transport, Session, Presentation, and Application), has been a cornerstone in network protocol design [17]. However, the resource limitations of WSNs, such as constrained energy,

processing power, and memory, necessitate a tailored approach [18]. Direct implementation of all seven OSI layers in WSNs proves impractical due to these constraints [18]. Consequently, WSN protocols typically prioritize the essential layers, namely the Physical, Data Link, Network, and Transport layers, while optimizing or omitting the higher layers [18]. This adaptation ensures efficient communication within the constraints of WSN environments, focusing on core functionalities like data transmission, error detection, routing, and reliable delivery [18].

## 2.3 Cross-Layer Optimization

Cross-layer optimization, a design paradigm that transcends the strict boundaries of the layered OSI model, has emerged as a critical approach to address the challenges faced by resource-constrained WSNs [19]. By enabling direct communication and cooperation between non-adjacent layers, cross-layer techniques empower WSNs to achieve enhanced energy efficiency, improved reliability, and better overall performance [19]. For instance, cross-layer protocols can leverage channel state information from the Physical layer to make informed routing decisions at the Network layer, thereby optimizing energy consumption and minimizing packet losses [20]. Moreover, information sharing between the Application and MAC layers can enable priority-based scheduling, ensuring timely delivery of critical data while conserving energy for less urgent transmissions [21]. However, it's important to acknowledge that cross-layer design introduces increased complexity and potential for protocol violations, warranting careful consideration of trade-offs and adherence to established standards [22].

## 2.4 Gateways in Wireless Sensor Networks

In WSNs, gateways play a crucial role as intermediaries between the resource-constrained sensor nodes and the external network or base station [1, 5, 13]. They are typically more powerful elements with greater energy, computational capabilities, and communication range than the sensor nodes [23]. Gateways are responsible for aggregating data from multiple sensor nodes, potentially performing data processing or filtering, and then transmitting the relevant information to the base station or other network entities [5]. In WSNs with limited coverage, gateways may communicate directly with sensor nodes in a single hop, like a star topology [14]. However, in larger networks, multi-hop communication is necessary, where gateways act as relay nodes, forwarding data from sensor nodes closer to the base station [24]. Gateways can also perform data aggregation, reducing redundant information before transmission, thus conserving energy. The design of gateways

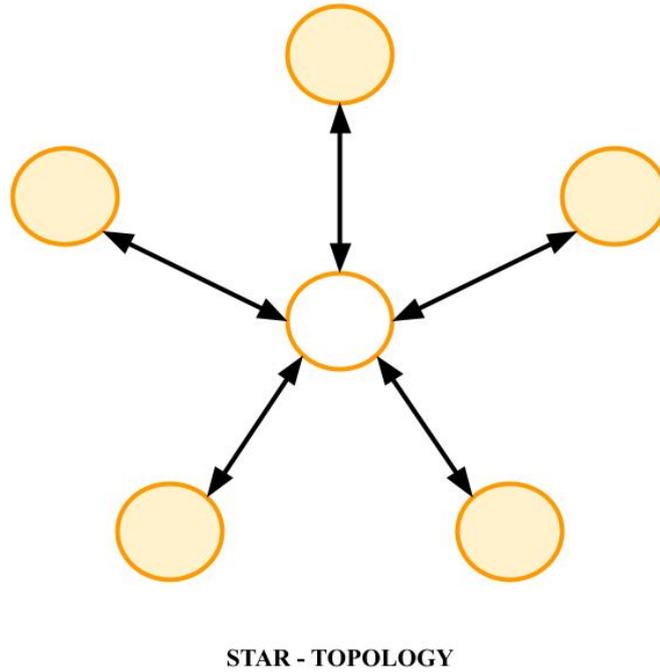
in WSNs is influenced by factors such as energy consumption, network topology, and the size of the area of interest [5].

## **2.5 Wireless Sensor Networks Topologies**

Topology control in WSNs is critical for optimizing network performance, enhancing energy efficiency, and ensuring robust connectivity. Various topologies have been developed, each with unique characteristics, advantages, and limitations. This review focuses on Star, Mesh, Tree, and Hybrid topologies, emphasizing their applications in IoT and healthcare, particularly for monitoring PD.

### **2.5.1 Star Topology**

Star topology is characterized by each sensor node communicating directly with a central base station. This setup simplifies network management and ensures low latency in data transmission, making it suitable for small-scale IoT deployments and localized monitoring such as healthcare systems. However, star topology introduces a single point of failure; if the base station fails, the entire network is compromised. Additionally, its scalability is limited as the base station can become a bottleneck under high traffic loads [17, 18, 13].



**Figure 2.2:** Star Topology in WSNs.

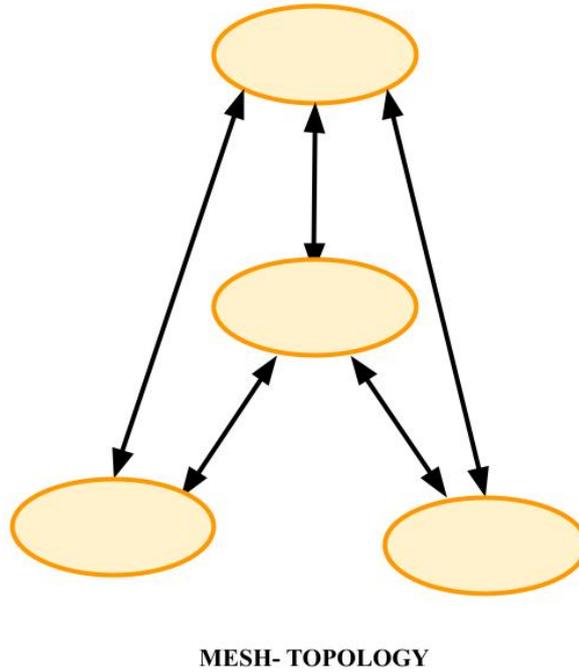
The energy consumption in star topology can be represented as:

$$E_{\text{total}} = \sum_{i=1}^n (E_{\text{tx},i} + E_{\text{rx},i})$$

where  $E_{\text{tx},i}$  and  $E_{\text{rx},i}$  denote the transmission and reception energy of node  $i$ , respectively [17, 13].

### 2.5.2 Mesh Topology

In contrast, mesh topology allows nodes to communicate with multiple other nodes, creating a robust and flexible network structure. This enhances fault tolerance and scalability, making it ideal for large-scale networks, industrial automation, and mission-critical applications. However, the increased complexity and higher energy consumption due to multiple communication paths are notable drawbacks [18, 13].



**Figure 2.3:** Mesh Topology in WSNs.

The total power consumption in mesh topology is given by:

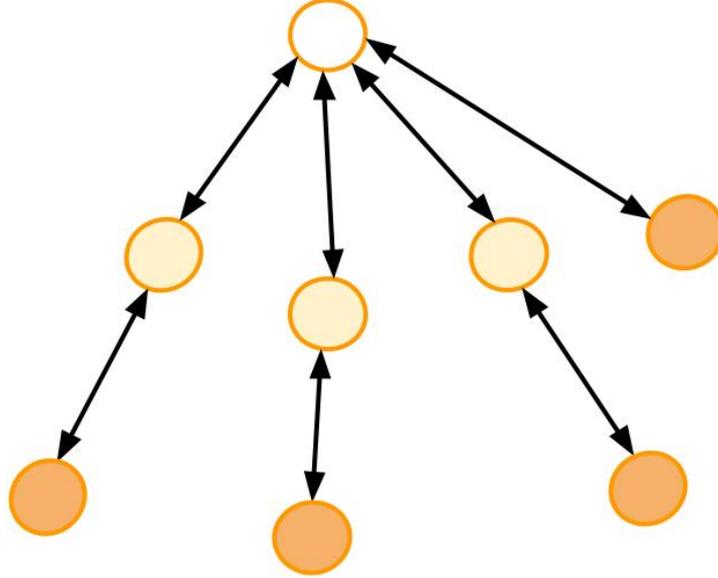
$$P_{\text{total}} = \sum_{i=1}^n (P_{\text{tx},i} + P_{\text{rx},i} + P_{\text{idle},i})$$

where  $P_{\text{tx},i}$ ,  $P_{\text{rx},i}$ , and  $P_{\text{idle},i}$  denote the transmission, reception, and idle power of node  $i$  [17, 13].

### 2.5.3 Tree Topology

Tree topology arranges nodes in a hierarchical structure, forming a tree-like network. This setup facilitates efficient data aggregation and reduces redundancy. In tree topology, each node, except the root, has a parent node to which it sends data. The term "hop" refers to the number of steps or "hops" data takes as it moves from a leaf node (at the edge of the network) to the root node (at the center). However, this topology is vulnerable to node failures and requires complex maintenance,

making it suitable for structured data collection environments such as environmental monitoring [18, 13].



**TREE-TOPOLOGY**

**Figure 2.4:** Tree Topology in WSNs.

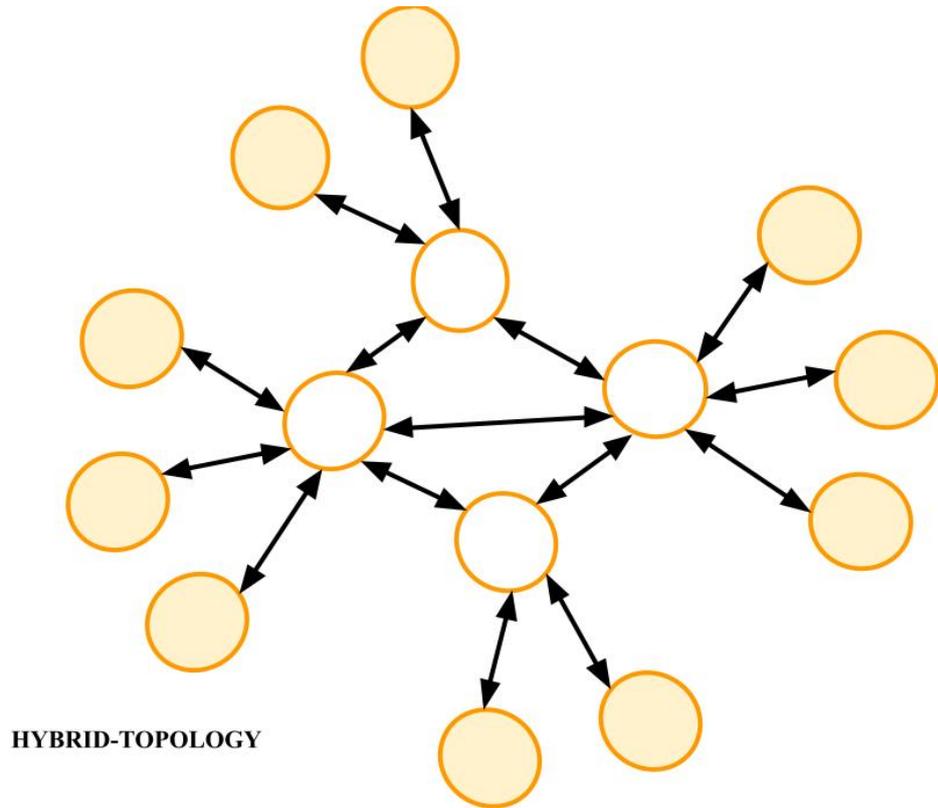
The energy consumption in tree topology can be calculated as:

$$E_{\text{tree}} = \sum_{i=1}^n (E_{\text{tx},i} + E_{\text{rx},i}) \times \text{Hop Count}$$

where Hop Count represents the number of hops from leaf nodes to the root node [17, 13].

### 2.5.4 Hybrid Topology

Hybrid topology combines elements of star, tree, and mesh topologies, leveraging their strengths to provide flexibility and improved performance. This approach is adaptable to various scenarios, making it suitable for versatile environments and large-scale heterogeneous networks. However, it also introduces design complexity and potential overhead [17, 18, 13].



**Figure 2.5:** Hybrid Topology in WSNs.

The energy consumption in hybrid topology can be expressed as:

$$E_{\text{hybrid}} = E_{\text{star}} + E_{\text{mesh}} - E_{\text{overlap}}$$

where  $E_{\text{overlap}}$  accounts for the overlapping energy consumption between star and mesh components [17, 18].

## 2.6 WSN Communication Standards and Specifications

WSNs rely on a variety of communication standards and specifications to ensure efficient and reliable data transmission. These standards address the unique challenges posed by WSNs, such as limited energy resources, low data rates, and the need for scalability.

### **2.6.1 IEEE 802.15.4**

IEEE 802.15.4 is a fundamental standard that defines the physical and Medium Access Control (MAC) layers for low-rate wireless personal area networks (LR-WPANs). It serves as the foundation for many WSN communication protocols, providing specifications for frequency bands (868 MHz, 915 MHz, and 2.4 GHz), modulation schemes, and data rates. The standard also defines two types of nodes: full-function devices (FFDs) and reduced-function devices (RFDs). FFDs can act as network coordinators or end devices, while RFDs are limited to being end devices. IEEE 802.15.4's low power consumption and flexibility make it a popular choice for WSNs in various applications [13, 5, 23].

### **2.6.2 ZigBee**

ZigBee is a widely adopted communication protocol built upon the IEEE 802.15.4 standard [25]. It is specifically designed for low-power, low-data-rate applications and is well-suited for WSNs due to its energy efficiency and ability to support mesh networking. ZigBee operates in the 2.4 GHz ISM band and offers a communication range of typically 10 meters, which can be extended through multi-hop communication [4]. It provides various network topologies, including star, tree, and mesh, allowing for flexible network configurations [3]. ZigBee's self-organizing and self-healing capabilities make it a robust and reliable choice for WSNs in diverse environments [15, 25].

### **2.6.3 Bluetooth and Bluetooth Low Energy (BLE)**

Bluetooth, a widely used wireless technology standard, enables short-range communication between devices [17]. While primarily designed for applications like audio streaming and data transfer between mobile devices, Bluetooth can also be utilized in WSNs, especially for scenarios that demand higher data rates [5]. Bluetooth Low Energy (BLE), a low-power variant of Bluetooth, is particularly well-suited for WSNs due to its reduced energy consumption and extended battery life [26]. BLE operates in the 2.4 GHz ISM band and offers a communication range of up to 100 meters [26]. Its low-power characteristics and compatibility with various devices make it a versatile option for WSNs in healthcare, fitness tracking, and smart home applications.

### **2.6.4 6LoWPAN**

6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) is a protocol that enables the transmission of IPv6 packets over LR-WPANs [17, 27]. This is crucial for WSNs that need to connect to the Internet or other IP-based networks [17,

27]. 6LoWPAN compresses IPv6 headers and fragments packets to fit the limited frame size of LR-WPANs, ensuring efficient communication [27]. It also provides mechanisms for addressing, routing, and security, making it a comprehensive solution for WSNs in the IoT ecosystem.

### 2.6.5 Other Emerging Standards

In addition to the established standards previously discussed, several emerging standards are gaining traction in the WSN domain. These include Thread, a newer protocol based on IEEE 802.15.4 that utilizes IPv6 addressing and offers robust security through AES encryption [26]; Z-Wave, a proprietary wireless communication protocol primarily used for home automation, known for its long-range capabilities and interoperability between devices from different manufacturers [26]; LoRaWAN (Long Range Wide Area Network), a low-power wide-area network technology that enables long-range communication between devices, making it suitable for WSNs deployed over large geographical areas [26]; and NB-IoT (Narrowband IoT) and LTE-M (Long Term Evolution for Machines), cellular technologies designed for low-power IoT devices, offering wide coverage and reliable connectivity for WSNs [26].

The provided Table ?? offers a comprehensive comparative analysis of various communication protocols pertinent to the Internet of Things (IoT). This analysis covers several critical attributes: transport protocols, messaging models, security measures, Quality of Service (QoS), application levels, data rates, power consumption, latency, and scalability. The protocols examined include CoAP, MQTT, XMPP, AMQP, DDS, 6LoWPAN, NB-IoT, 5G NR, BLE, Zigbee, Thread, IEEE 802.15.4, Z-Wave, and LoRaWAN.

The transport protocols range from UDP and TCP to proprietary protocols, which form the foundation of the communication mechanisms. Messaging models differ, encompassing request/response, publish/subscribe, and client/server architectures, each influencing data exchange methods. Security implementations feature DTLS 1.3, TLS 1.3, SASL, IPsec, and various AES encryption standards, ensuring data integrity and confidentiality.

QoS features are essential for maintaining reliable communication, including block transfer, QoS levels, stream management, fine-grained QoS, and power-saving modes. Application levels extend across devices, gateways, and platforms, indicating the protocols' adaptability to different network layers. Data rates vary from low (<1 Mbps) to high, affecting communication speed. Power consumption is categorized from very low to high, which is crucial for battery-operated IoT devices. Latency and scalability are also assessed, reflecting the protocols' efficiency and capacity to manage network growth and complexity.

This detailed comparison underscores the importance of selecting the appropriate

protocol based on specific application requirements, balancing factors such as security, power efficiency, and network performance. This selection process is pivotal for optimizing the performance and reliability of IoT networks [13, 15, 25, 26, 5, 23, 3].

**Table 2.1:** Comparative Analysis of Communication Protocols - Part 1

<b>Protocol</b>	<b>Transport Protocol</b>	<b>Messaging Model</b>	<b>Data Rate</b>	<b>Latency</b>	<b>Scalability</b>
CoAP [5]	UDP	Request/Response	Low (<1 Mbps)	Low	Moderate
MQTT [28]	TCP	Publish/Subscribe, Username/Password	Medium	Low	High
XMPP [5]	TCP	Publish/Subscribe, Client/Server	Medium	Medium	High
AMQP [28]	TCP	Publish/Subscribe, Point-to-Point	Medium	Medium	High
DDS [29]	UDP (Optional TCP)	Publish/Subscribe	High	Very Low	High
6LoWPAN [27]	UDP	Adaptation Layer	Low (<1 Mbps)	Low	Moderate
NB-IoT [30]	UDP	Service Layer	Medium	Medium	High
5G NR [30]	UDP	Service Layer	High	Low	High
BLE [26]	Proprietary	GATT	Low	Low	Moderate
Zigbee [15]	Proprietary	Star/Mesh/Tree	Low	Low	High
Thread [29]	IEEE 802.15.4	Mesh	Low	Low	High
Z-Wave [5]	Proprietary	Mesh	Low	Low	Moderate
LoRaWAN [1]	Proprietary	Star	Low	Low	High

**Table 2.2:** Comparative Analysis of Communication Protocols - Part 2

Protocol	Security	QoS	Application Level	Power Consumption
CoAP [5]	DTLS 1.3	Observe, Block Transfer	Device, Gateway	Very Low
MQTT [28]	TLS 1.3	QoS Levels (0, 1, 2), Last Will	Device, Gateway	Medium
XMPP [5]	TLS 1.3, SASL	Stream Management, Message Prioritization	Device, Gateway, Platform	Medium
AMQP [28]	TLS 1.3, SASL	Transactions, Message Durability	Device, Gateway, Platform	Medium
DDS [29]	Fine-Grained QoS (Reliability, Deadline, Liveliness)	Fine-Grained QoS (Reliability, Deadline, Liveliness)	Device, Gateway, Platform	Medium
6LoWPAN [27]	IPsec	Header Compression, Fragmentation	Device, Gateway	Low
NB-IoT [30]	LTE/5G Security	Power Saving Mode, eDRX/PSM	Device, Gateway	Very Low
5G NR [30]	5G Security (Network Slicing, Authentication)	URLLC, eMBB, mMTC	Device, Gateway	Medium
BLE [26]	AES-CCM	Adaptive Frequency Hopping, Power Control	Device	Very Low
Zigbee [15]	AES-128	Low Latency, Green Power	Device, Gateway	Low
Thread [29]	AES-128	Low Latency, IP Routing	Device, Gateway	Very Low
Z-Wave [5]	S2 Security Framework	Low Power, Reliable	Device, Gateway	Very Low
LoRaWAN [1]	AES-128	Adaptive <sup>17</sup> Data Rate, Low Power	Device, Gateway	Very Low

As illustrated in Tables 2.1 and 2.2, various communication protocols exhibit distinct characteristics in terms of transport mechanisms, security features, quality of service, and scalability.

## 2.7 Wireless Body Area Networks (WBANs)

WBANs are similar to WSNs but are specifically designed for use on and around the human body. While both involve a network of sensors that collect and transmit data, WBANs are tailored to monitor physiological parameters continuously and in real-time. These networks face unique challenges due to the dynamic nature of the human body, including variable sensor positioning and movement [31].

WBANs play a pivotal role in modern healthcare by enabling continuous monitoring of physiological parameters through a network of tiny biomedical sensors. These sensors, which possess limited energy, memory, and computational capabilities, are strategically positioned on or around the human body. Efficient management and control of these networks are challenging, particularly in large-scale deployments for remote healthcare monitoring. The integration of IoT and cloud computing technologies offers promising solutions by providing extensive data storage, computational power, and processing utilities at lower costs. This technology, alongside appropriate sensors to extract the data, is particularly beneficial for elderly individuals and patients with chronic conditions such as PD [31, 32, 33].

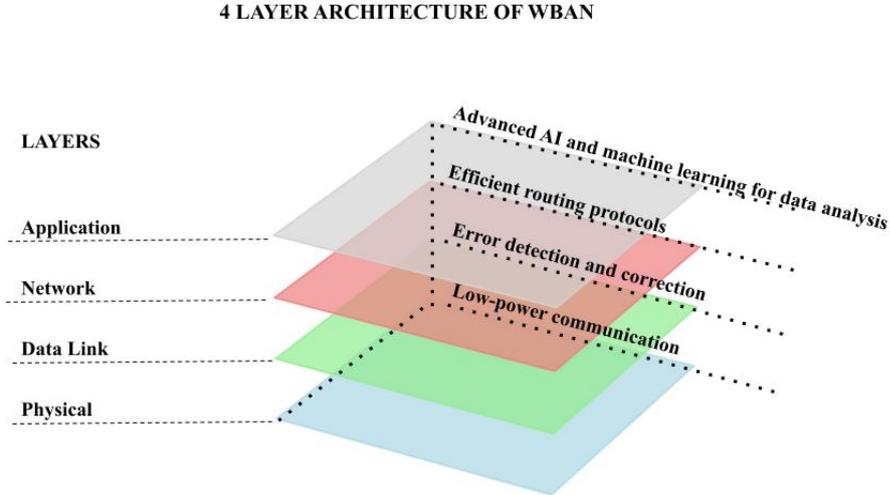
### 2.7.1 Architecture

The design and implementation of WBANs for monitoring chronic diseases such as PD rely heavily on the effective use of specific OSI model layers to ensure efficient and reliable data transmission [34]. The physical layer focuses on low-power communication to extend the battery life of wearable sensors. The data link layer is crucial for error detection and correction, ensuring the accuracy and integrity of the transmitted health data. Efficient routing protocols in the network layer handle the dynamic and mobile nature of WBANs, facilitating continuous and real-time monitoring. The application layer leverages advanced AI and machine learning algorithms for data analysis, providing real-time insights and alerts critical for managing PD [35, 7, 36].

Recent advancements highlight the benefits of adopting a four-layer architecture, which has become the most common approach in WBAN design for chronic disease monitoring. This architecture effectively integrates functionalities across the physical, data link, network, and application layers, balancing efficiency and reliability. This approach ensures robust data transmission and real-time analysis, making it highly suitable for chronic disease management. Studies have shown that this four-layer model enhances overall system performance and patient care

outcomes by addressing key challenges such as energy consumption, data integrity, and real-time processing [10, 37, 33].

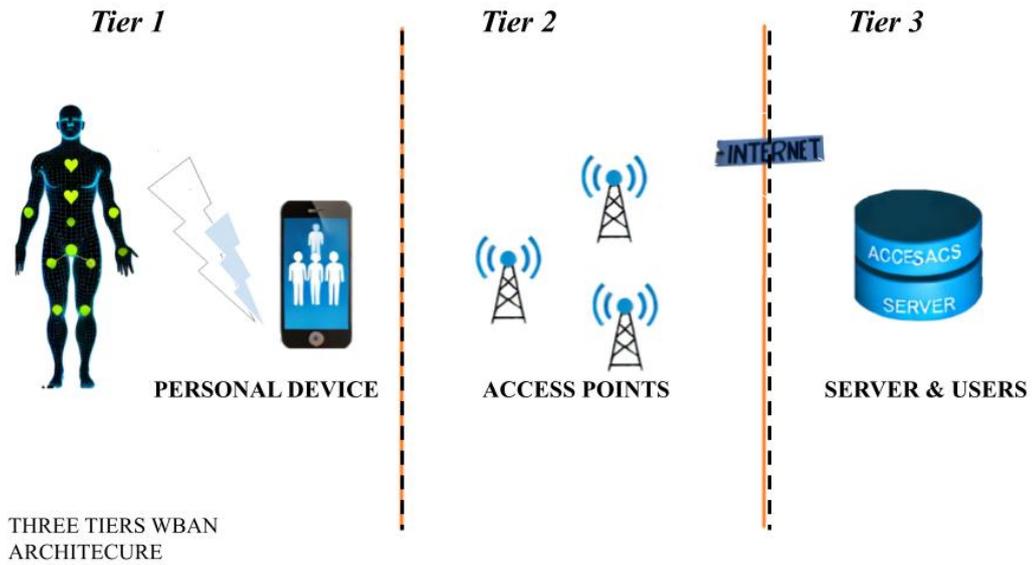
The figure below illustrates this four-layer architecture, detailing the specific functions of each layer:



**Figure 2.6:** Four-layer architecture of WBANs for chronic disease monitoring.

### 2.7.2 Three-Tier Architecture

The architecture of WBANs is systematically categorized into three tiers: intra-WBAN, inter-WBAN, and beyond-WBAN. As illustrated in the provided figure [38], intra-WBAN involves communication between sensors placed on or around the human body and a personal device. These sensors capture physiological data and transmit it either directly to the personal device or through intermediate nodes. Inter-WBAN encompasses communication between the personal device and access points (AP) using wireless technologies such as Bluetooth, ZigBee, or Wi-Fi, thereby serving as a bridge to broader networks [33]. Beyond-WBAN pertains to communication between the AP and remote medical centers, where data from multiple WBANs are stored and processed in cloud data centers for access by healthcare professionals [35, Ch. 2].



**Figure 2.7:** Three-tier architecture for WBANs

This three-tier architecture enables continuous health monitoring, reduces the necessity for hospital stays, and facilitates timely medical feedback, proving highly beneficial for managing chronic diseases [38]. Advances in microprocessors, wireless interfaces, and battery technologies are critical for the widespread adoption of WBANs, addressing the increasing demand for efficient and cost-effective health monitoring solutions. Specific frequency bands have been allocated to WBANs to ensure reliable communication and minimize interference with other wireless technologies. Recent innovations include the integration of Low Power Wide Area Network (LPWAN) technologies, such as NB-IoT and LTE-M, alongside the exploration of innovative energy harvesting techniques that provide sustainable power sources for WBAN sensors, thereby reducing dependency on batteries and extending the operational lifespan of the network [35, 33, 38].

## 2.8 Routing in WBANs



**Figure 2.8:** Challenges faced during routing in WBANs

Generally, routing is the process of identifying the most efficient path for data to traverse from one node to another within a network. However, networks face several challenges during this process. The figure [39] shows the primary challenges faced during routing in networks, including limited resources, security, network partitioning, quality of service (QoS), and energy efficiency [39]. Each challenge impacts the reliability and efficiency of data transmission across the network [39, 16].

Additionally, the optimal routing protocol for a WBAN depends on multiple

factors, including the network size, node mobility, and link quality [40, 39]. To address these issues, routing protocols should be developed to eliminate or minimize these obstacles. Various routing protocols have been developed to address these challenges, which we will discuss in the following section.

### **2.8.1 Network Partitioning**

WBANs often experience network partitioning due to the short transmission range and postural changes. This can disrupt data routing to the coordinator. Protocols addressing network partitioning typically incorporate backup pathways to ensure data transmission continuity. For instance, some approaches use body-coupled communication (BCC) as a secondary pathway, leveraging the human body as a medium to maintain connectivity when the primary RF link fails [39]. Each sensor node may have a main path and a backup path; the backup path is used in emergencies or when the primary path fails, ensuring robust communication [6].

### **2.8.2 Energy Efficiency**

Energy efficiency is critical in WBANs due to the difficulty of replacing batteries in body-embedded nodes. Energy consumption is predominantly due to inter-node communication rather than data processing [38]. Dynamic routing protocols, which adapt the data paths based on current network conditions, can enhance energy efficiency and extend network lifespan [41, 6]. For example, frameworks that balance QoS constraints and dynamic link features have shown promise in improving energy management in WBANs [6]. The lifespan of a network is often defined as the period from deployment until the first node's battery is exhausted [6].

### **2.8.3 Quality of Service (QoS)**

Meeting QoS requirements is essential in WBANs, especially for critical medical data [34, 32, 6]. QoS parameters include packet delivery ratio, throughput, packet drop ratio, and latency. Different types of medical data, such as normal, emergency, delay-sensitive, and reliability-sensitive data, necessitate distinct QoS considerations [34, 31]. Systems designed to maximize energy efficiency while ensuring QoS typically prioritize the delivery of emergency packets over regular data to meet stricter performance criteria [6]. For instance, a system that adjusts transmission rates dynamically to maintain QoS performance in terms of packet loss rate (PLR), latency, and throughput is critical [6].

### **2.8.4 Privacy and Security**

Ensuring data privacy and security is a fundamental requirement in WBANs. Traditional security measures are often unsuitable due to the limited resources of WBAN nodes. Effective routing protocols must incorporate encryption and authorization mechanisms to protect sensitive medical data from unauthorized access [41]. Techniques like phantom routing can enhance source location anonymity by creating decoy data paths, thus increasing overall network security [39]. Ensuring that only authorized personnel can access patient data is crucial, given the sensitivity of medical information [41, 39].

### **2.8.5 Limited Resources**

The restricted resources of WBANs, such as short RF transmission range, low bandwidth, limited computing power, and inadequate storage capacity, necessitate careful protocol design. Routing protocols must efficiently manage these constraints to maintain network performance. Developing protocols that can dynamically adapt to varying conditions, minimizing the impact of resource limitations, is widely common [6, 39]. When designing WBAN routing protocols, researchers must consider these limitations to create efficient and reliable communication systems.

## 2.9 Routing Protocols

[Note: Write a short paragraph explaining the importance and types of routing protocols in WBANs. Include any necessary introductory information before detailing specific protocols.]

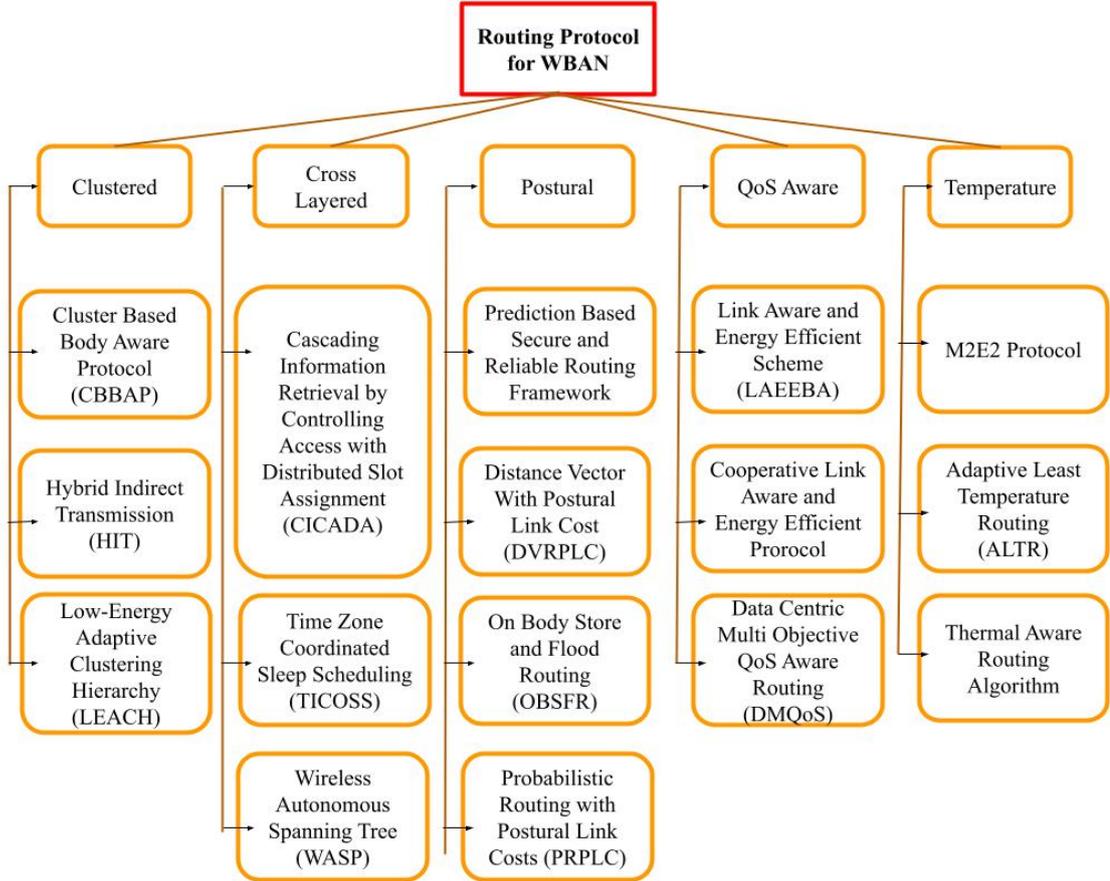


Figure 2.9: Routing Protocols for WBAN

### 2.9.1 Clustering in Wireless Body Area Networks

Clustering is an essential technique in WBANs designed to enhance network efficiency and reliability by optimizing data transmission and energy consumption [33, 16]. Clustering involves organizing sensor nodes into distinct groups, each managed by a Cluster Head (CH). The CH is responsible for aggregating data from all nodes within its cluster and forwarding this data to higher-level nodes, such as Gateways (GW), which then transmit the information to remote Medical

Servers (MS). This hierarchical organization reduces communication overhead and energy consumption by minimizing the distance data must travel and consolidating transmissions, thereby enhancing overall network performance [34].

### **2.9.2 Intra-cluster**

Intra-cluster communication involves direct communication between nodes and their respective CHs using low-power transmissions. This method conserves energy and minimizes interference with other clusters [RN6].

### **2.9.3 Inter-cluster Communication**

Inter-cluster communication entails CHs communicating with one another or directly with the sink using higher transmission power, facilitating efficient multi-hop communication across the WBAN [26].

### **2.9.4 Challenges in Clustering**

Despite these advantages, implementing clustered routing protocols in WBANs is not without its challenges. One of the primary difficulties lies in the complexity of CH selection. Developing dynamic CH selection algorithms that adapt to real-time network conditions can be computationally intensive. Furthermore, CHs can become energy bottlenecks due to their additional responsibilities, necessitating efficient energy management strategies. As the number of nodes increases, maintaining efficient communication and energy management becomes more challenging, highlighting issues related to scalability and overhead. Adaptability to dynamic environments is another critical challenge. WBANs operate in highly dynamic settings, necessitating protocols that can swiftly adapt to changes in network topology and node mobility [26, 33, 34, 16].

### **2.9.5 Trust-Based Energy-Efficient and Reliable Communication Scheme**

The Trust-Based Energy-Efficient and Reliable Communication Scheme (Trust-Based ERCS) leverages clustering to ensure that data transmission is both secure and efficient [42, 24]. This trust-based selection process enhances the overall robustness and efficiency of the WBAN, ensuring secure and reliable data transmission while conserving energy resources [42, 24].

### **2.9.6 Distributed Energy-Efficient Clustering and Routing (DECR)**

The DECR (Distributed Energy-Efficient Clustering and Routing) protocol exemplifies a sophisticated clustering methodology that leverages two-hop neighbor information to improve network stability and energy efficiency. In networking, a "hop" refers to the passage of data from one network node to the next. In the context of WBANs, minimizing the number of hops can significantly reduce energy consumption and latency, as each hop typically requires additional power and time for data transmission [34, 42].

By prioritizing nodes with optimal connectivity and energy levels, DECR balances energy consumption across the network and extends network lifetime [34].

### **2.9.7 Genetic Algorithm-Based CH Selection**

Similarly, the scheme proposed by [24] employs a genetic algorithm to optimize the selection of CHs based on multiple factors, including residual energy, energy consumption rates, distance to the SDN controller, signal-to-noise ratio, and path loss. This optimization process minimizes network delay and enhances data transmission efficiency [24]. The genetic algorithm's ability to dynamically adapt to changing network conditions results in significant improvements in network stability and reliability, making ERQTM particularly effective in maintaining prolonged network lifetime and high-quality service in WBANs [24].

### **2.9.8 Energy Trust Assessment Scheme (ETAS)**

Furthermore, [16] (ETAS) introduces a multi-faceted trust evaluation framework that incorporates communication trust, data trust, and energy trust. This clustering approach significantly improves data transmission and resource utilization. By leveraging successful interaction rates and historical misbehavior, ETAS dynamically adjusts trust parameters to enhance reliability and security while maintaining low resource consumption. Packet delivery ratio (PDR), showing an improvement of 11% and 16.66% over PSTRM and BAN-TRUST respectively, when 10% of nodes are selfish, and even higher improvements as the percentage of malicious nodes increases. These results underscore the significant benefits of the clustering mechanism within ETAS, making it an effective solution for secure and efficient WBANs [16].

### **2.9.9 Trust-based Intrusion Detection and Clustering**

Another approach called "Trust-based Intrusion Detection and Clustering for Wireless Body Area Networks" has been proposed to facilitate efficient transmission of

vital medical data in open environments. The cluster head in each group is selected using a multi-objective firefly algorithm. This method employs hybrid encryption to protect sensitive data and utilizes target functions to boost throughput. Simulations using NS-2 show promising results in terms of packet delivery ratio (PDR), delay, precision, and recall [43].

### 2.9.10 Summary of Clustering Benefits

Clustering plays a pivotal role in managing resource constraints and enhancing the robustness of WBANs. By systematically selecting CHs based on trust and efficiency metrics, clustering ensures reliable data transmission, which is crucial for healthcare applications. The hierarchical structure provided by clustering reduces the frequency of long-distance transmissions, thereby conserving energy and extending the operational life of sensor nodes. This is particularly important in WBANs, where sensor nodes are often resource-constrained and energy efficiency is critical to sustaining long-term operation [34], [42], [24], [16], [43].

**Table 2.3:** Comparative Analysis of Clustering Protocols - Part 1

Protocol	Key Features	Advantages
LEACH [34, 42]	Randomized CH selection, periodic rotation	Simplicity, energy efficiency
HEED [24]	Residual energy and node proximity in CH selection	Improved stability and efficiency
TARA [16]	Thermal awareness in routing decisions	Avoids node overheating
EEBCDA [43]	Energy-efficient clustering and data aggregation	Balances energy consumption
DECR [44]	Two-hop neighbor-based clustering, dynamic CH selection	Enhanced PDR, energy efficiency, cluster lifetime
CBBAP [14]	Efficient clustering for enhanced transmission and energy efficiency	Energy-efficient, suitable for body area networks
HIT [45]	Combines direct and indirect transmission strategies	Optimized routing, balances energy consumption and data reliability

**Table 2.4:** Comparative Analysis of Clustering Protocols - Part 2

<b>Protocol</b>	<b>Limitations</b>	<b>Performance Metrics (Simulation)</b>
LEACH [34, 42]	Lacks WBAN-specific considerations	Moderate energy efficiency, moderate network lifetime
HEED [24]	Not optimal for dynamic environments	High energy efficiency, longer network lifetime
TARA [16]	Not focused on energy balancing	High network lifetime, temperature management
EEBCDA [43]	Complexity in implementation	High energy efficiency, balanced energy load
DECR [44]	Complexity in dynamic environments	Highest PDR, lowest energy consumption, highest residual energy, longest cluster lifetime
CBBAP [14]	Limited to specific scenarios	Moderate energy efficiency, suitable for targeted applications
HIT [45]	Complex implementation, limited to certain environments	High energy efficiency, reliable data transmission

### 2.9.11 Cross-Layered Routing Protocol

Clustering plays a pivotal role in managing resource constraints and enhancing the robustness of Wireless Body Area Networks (WBANs). By systematically selecting Cluster Heads (CHs) based on trust and efficiency metrics, clustering ensures reliable data transmission, which is crucial for healthcare applications. The hierarchical structure provided by clustering reduces the frequency of long-distance transmissions, thereby conserving energy and extending the operational life of sensor nodes. This is particularly important in WBANs, where sensor nodes are often resource-constrained and energy efficiency is critical to sustaining long-term operation [34, 42, 24, 16, 43].

**Table 2.5:** Comparative Analysis of Clustering Protocols - Objectives

Protocol	Objectives
CICADA[46]	Efficient data transmission and slot assignment for optimized communication
TICOSS[46]	Energy efficiency through coordinated sleep scheduling
WASP[46]	Creation of efficient communication paths using spanning trees
AODV- ECO[46]	Reduces control overhead and energy consumption, improves QoS
PCLRP[46]	Prioritizes data based on urgency to improve QoS for critical health data

**Table 2.6:** Comparative Analysis of Clustering Protocols - Limitations

Protocol	Limitations
CICADA[46]	Increased complexity in slot management, potential synchronization issues
TICOSS[46]	Potential delays in data transmission due to sleep schedules
WASP[46]	Overhead in maintaining the spanning tree structure, may not adapt quickly to network changes
AODV- ECO[46]	Requires careful tuning to balance control overhead and data delivery performance
PCLRP[46]	Complexity in managing priorities and potential higher energy consumption

### 2.9.12 Security Responsive Routing Protocol

In the context of Internet of Things (IoT) networks, Quality of Service (QoS) is crucial due to the diverse and often stringent requirements of different applications, such as multimedia streaming, healthcare, and surveillance [5, 4]. Similarly, in WBANs, QoS-aware routing protocols are designed to ensure that the performance of critical applications is maintained by managing network resources and traffic effectively [39].

One of the primary goals of a security-aware routing protocol within WBANs is to ensure privacy and reliable data routing [6]. Medical data from patients are periodically monitored using body sensor devices and subsequently categorized based on content and sensitivity level. This categorized data is then transmitted from the sink node to the medical center, enabling medical professionals to remotely monitor and treat patients [47]. Various algorithms and protocols play significant roles in enhancing QoS and security in WBANs. Tables 2.7 and 2.8 summarize

some key algorithms, their objectives, and their limitations [39, 47, 48, 41, 6].

**Table 2.7:** Comparative Analysis of Routing Protocols - Objectives

Protocol	Objectives
EPPA[39]	Privacy-preserving data aggregation
MPPA[39]	Secure data aggregation using non-addition methods
P-AEEF[48]	Protect patient data from unauthorized access
LAEEBA[41]	Maintain link quality and optimize energy consumption
DMQoS[6]	Address multiple QoS objectives like minimizing delay and maximizing throughput
CLEE[6]	Enhance link reliability and reduce energy usage through cooperative strategies

**Table 2.8:** Comparative Analysis of Routing Protocols - Limitations

Protocol	Limitations
EPPA[39]	Supports only addition aggregation, increases communication overhead
MPPA[47]	Higher energy consumption than EPPA due to the complexity of using multiple aggregation methods
P-AEEF[48]	High energy consumption due to the use of intensive security measures, potentially reducing the lifespan of sensor nodes
LAEEBA[41]	May not address all types of QoS requirements simultaneously
DMQoS[6]	High complexity and may require significant computational resources
CLEE[6]	Complexity of implementation and potential synchronization issues

### 2.9.13 Temperature Aware Routing Protocol

Radio signals from wireless technologies generate magnetic and electric fields, increasing temperature in implanted sensor nodes, potentially damaging tissues and organs [39]. The specific absorption rate (SAR) quantifies this absorbed radio frequency [39]. Temperature-aware routing protocols aim to mitigate this temperature increase [39, 41]. The Least Total Route Temperature Protocol (LTRT) is highly effective, while the Temperature Aware Routing Algorithm (TARA) is less so [41].

Thermal-aware routing is crucial for WBANs as biosensors emit potentially harmful electromagnetic radiation during communication [41]. The Thermal-Aware

Routing Algorithm (TARA) identifies overheated nodes and reroutes data but faces challenges in network lifetime and reliability [41]. The Least Total Route Temperature (LTRT) algorithm, combining shortest-path and least temperature routing, selects routes based on the lowest temperature path, considering dynamic temperature changes in nodes [41].

### **2.9.14 Postural-Movement Based Routing Protocol**

Network partitioning in WBANs, caused by body movements, can disrupt data links and hinder routing [39]. Posture-based routing protocols aim to minimize delays in data transmission from sensor nodes to sink nodes, adapting to these changes in connectivity [39].

On-Body Store and Flood Routing (OBSFR) is one such protocol, designed to reduce energy consumption and data delays by sending multiple copies of packets through different paths, ensuring reliable transmission despite potential network partitioning [39]. Other posture-based protocols establish stable paths between nodes and the base station, considering the dynamic nature of the body to minimize transmission costs [41]. The opportunistic routing algorithm further addresses this issue by leveraging relay nodes to simplify data transmission between sensors and the sink hub on the wrist, adapting to changes in wrist position during movement [41]. In Figure ??, each subplot corresponds to one of the activities including standing, sitting, walking, and sleeping. The variations are in RSS [46].

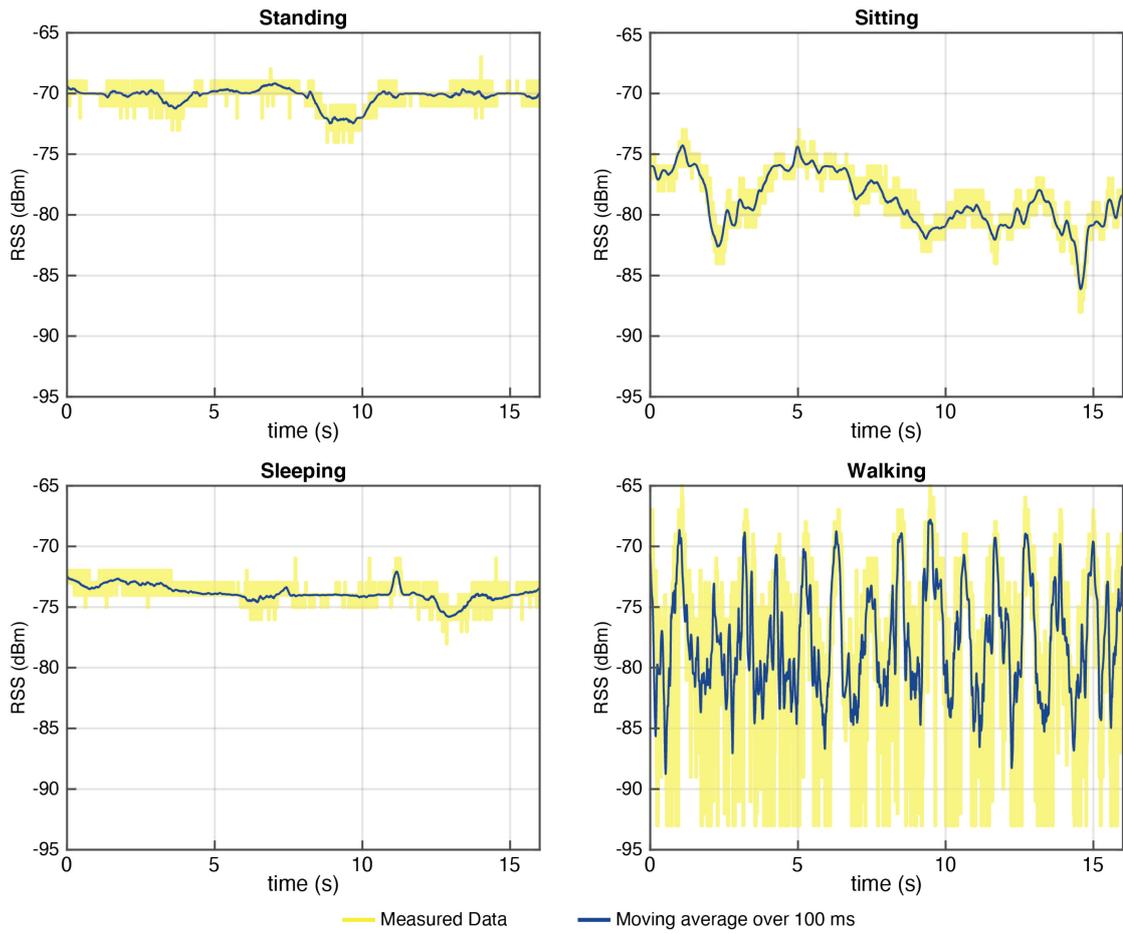


Figure 2.10: RSS Variations Across Different Activities

## Chapter 3

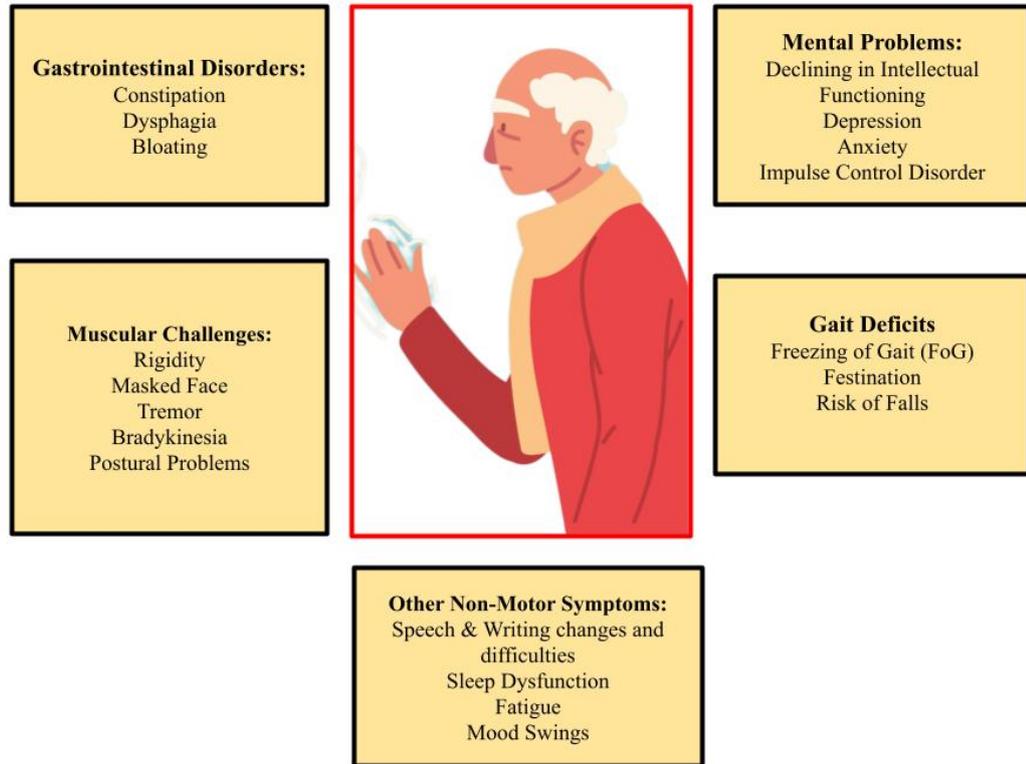
# Conceptual Framework and System Design

### 3.1 Parkinson's Disease (PD)

Parkinson's Disease (PD) is a prevalent neurodegenerative disorder, currently ranked as the second most common disease globally, significantly impacting the elderly population, particularly individuals over the age of 60 [49, 50]. The exact cause of PD remains unknown while generic, environmental factors and age play important role in the risk of disease progression [50]. PD is characterized by a debilitating combination of motor and non-motor symptoms. Motor impairments such as bradykinesia (slowness of movement), rigidity, resting tremor, and gait disturbances significantly impact patients' quality of life [51, 52, 53]. Gait abnormalities, including reduced stride length, shuffling steps, and abnormal plantar force distribution, are particularly problematic and can lead to increased falls and injuries [51]. Additionally, PD patients often experience non-motor symptoms such as sleep disorders, nocturnal hypokinesia (reduced nighttime movement), and morning akinesia, which can further diminish their overall well-being [53]. A list of most common motor and non-motor symptoms is shown in Figure 3.1 below.

### 3.2 Challenges in PD Management

Managing PD presents multifaceted challenges attributable to the disease's intricate and progressive nature. This section elucidates the primary obstacles encountered in PD management, encompassing symptom heterogeneity, limitations of current assessment tools, and the complexities associated with medication side effects and individualized treatment strategies.



**Figure 3.1:** Most Common Motor and Non-Motor Symptoms of Parkinson's Disease

### 3.2.1 Heterogeneity and Progression of Symptoms

PD symptoms vary significantly between individuals and can evolve unpredictably over time [52, 53]. This heterogeneity poses challenges for both diagnosis and treatment, necessitating personalized approaches to address the unique needs of each patient [52]. Moreover, the progressive nature of PD implies that symptoms intensify over time, mandating continual adjustments to therapeutic interventions and necessitating ongoing monitoring to track disease progression accurately [53].

### 3.2.2 Limitations of Current Assessment Tools

Traditional clinical assessments for PD predominantly rely on subjective evaluations and patient-reported outcomes, which may not fully capture the breadth and depth of motor and non-motor symptoms [53]. Laboratory-based evaluations of gait and balance, while informative, may not capture the full extent of functional

impairments in real-world settings [51]. Furthermore, Sleep disorders are frequently underdiagnosed due to the reliance on subjective sleep diaries and the limited availability of specialized sleep studies [53]. These limitations underscore the imperative for more objective, continuous, and real-time assessment tools to enhance the accuracy and comprehensiveness of PD symptom monitoring.

### **3.2.3 Medication Side Effects and Individualized Treatment**

Pharmacological interventions, particularly the administration of levodopa, are efficacious in managing motor symptoms during the early stages of PD. However, prolonged use of such medications is often accompanied by adverse effects, including dyskinesia (involuntary movements), confusion, and hallucinations [52]. These side effects complicate long-term management, necessitating the development of personalized treatment plans that judiciously balance the therapeutic benefits of medications with their potential risks. Individualized treatment strategies are essential to optimize symptom control while minimizing adverse effects, thereby enhancing the overall quality of life for PD patients [52].

## **3.3 Current Trends in Technology**

Advancements in technology are increasingly being harnessed to ameliorate the management of PD through innovative solutions. Wearable sensors and the Internet of Things (IoT) are at the forefront of these developments, facilitating continuous real-world monitoring of both motor and non-motor symptoms [54, 4, 38, 10]. This shift addresses the limitations of traditional clinical assessments and the need for personalized treatment approaches [55, 10].

In a systematic literature review (SLR) conducted in [56], the efficacy of devices equipped with Inertial Measurement Units (IMUs) and other sensors was examined, highlighting their capacity to continuously monitor patient movements and provide detailed data on motor symptoms such as tremors, bradykinesia, and gait abnormalities. These devices enable real-time tracking and assessment of PD symptoms, thereby facilitating more accurate and timely medical interventions. The integration of such personalized monitoring solutions is paramount for achieving optimal symptom control and enhancing patient outcomes [56, 39, 36].

## **3.4 Introduction to the PRIMULA Project**

Recent advancements in IoT-based healthcare and WBAN have significantly addressed gaps in PD management. Wearable devices offer personalized and empowering solutions for patients by leveraging cutting-edge technologies. These

devices integrate advanced sensors, miniaturized electronics, and sophisticated algorithms to collect, transmit, and analyze health data, enabling proactive health management and informed decision-making [22, 19].

### 3.5 Problem Statement

This thesis work, the PRIMULA, addresses the critical challenges inherent in WBAN designs through a comprehensive review and the selection of effective protocols across various layers of the OSI model for asynchronous sensor networks designed for conceptual wearable devices. This conceptual framework integrates the Network Time Protocol (NTP) for precise time synchronization and the Message Queuing Telemetry Transport (MQTT) protocol for reliable real-time data transmission. Achieving precise synchronization between asynchronous sensor nodes is essential in applications like motion capture or gait analysis, where accurate timing and coordination between multiple IMUs are crucial for reconstructing movement patterns [57, 58]. In real-world applications, synchronization issues such as clock drift, network dependency, and elevated power consumption present significant obstacles to maintaining accurate timing across distributed sensor networks. Existing solutions often face limitations such as clock drift, network dependency, and increased power consumption, thereby complicating the maintenance of precise synchronization.

In real-world applications, synchronization issues such as clock drift, network dependency, and elevated power consumption present significant obstacles to maintaining accurate timing across distributed sensor networks. NTP is selected for its high accuracy in synchronizing clocks across a network, typically achieving synchronization within milliseconds. This level of accuracy is vital for ensuring accurate data correlation from multiple sensors. Furthermore, NTP is widely adopted, scalable, and well-suited for environments demanding precise timing, such as WBANs. The PRIMULA system employs a laptop as the NTP server to provide accurate timestamps, thereby ensuring synchronized data collection from sensor nodes. This approach is rigorously tested and validated through experimental setups, demonstrating efficient synchronization and data transmission with minimal delay. Although a hybrid approach combining NTP with beaconing might offer enhanced synchronization, it is not implemented in the current project [57, 59].

Wi-Fi is chosen for its ability to handle higher data rates and provide stable connections over relatively long distances, making it suitable for continuous monitoring in WBANs. Its built-in capabilities in the Raspberry Pi Pico W enhance system reliability without requiring additional communication modules. Compared to BLE, Wi-Fi offers superior data rate, range, and security, which are critical for high-data-rate applications despite BLE's low latency and power consumption

advantages [25, 5, 32].

To manage continuous data streams efficiently, a circular buffer is implemented, preventing data loss and ensuring smooth data processing. The MQTT protocol, known for its lightweight and low-bandwidth characteristics, supports reliable communication through various QoS levels, making it ideal for real-time monitoring applications. The integration of a watchdog timer further enhances system reliability by monitoring operations and resetting the microcontroller during anomalies, ensuring continuous operation. Extensive testing validates the system's performance, demonstrating its capability to achieve reliable data transmission with minimal delay, thereby making it suitable for real-time monitoring of PD patients. Detailed descriptions of the testing and validation processes are elaborated in Chapter 4 [58].

In essence, real-time monitoring and data aggregation are critical for effective patient care [36]. MQTT's efficiency in low-bandwidth conditions and its ability to handle asynchronous nodes make it an excellent choice for this project, providing a comprehensive view of the patient's condition. For future work, cloud-based processing could further enhance scalability and flexibility, enabling continuous monitoring and timely interventions. Based on real-world implementations, MQTT facilitates scalable and resilient communication in IoT ecosystems, supporting both single-node and multi-node deployments. Future work could focus on patient data from real-world scenarios, testing the system with additional nodes equipped with IMUs and modules for the central node, and exploring hybrid communication protocols alongside routing and aggregating algorithms to optimize power consumption and improve overall performance.

## 3.6 System Design and Architecture

The proposed system integrates hardware and software components designed to meet the project's objectives. A modular approach is adopted to facilitate scalability, flexibility, and ease of integration with additional sensors and functionalities in future work.

### 3.6.1 Hardware Components

At the core of the Primula framework is the Raspberry Pi Pico W microcontroller, which is chosen for its cost-effectiveness and solid capabilities in real-time IoT applications. At the heart of the Pico W is the ARM Cortex M0+ processor, renowned for its efficiency in constrained embedded applications, the smallest ARM processor available [60]. This microcontroller integrates several key features that make it particularly suited for the PRIMULA.

First and foremost, the Raspberry Pi Pico W boasts an on-board ADC, allowing for precise conversion of analog signals to digital data. In fact, this capability is crucial for the accurate processing of sensor inputs, ensuring high data integrity. Although the ADC relies on the 3.3V Switching Mode Power Supply (SMPS) output for accuracy, performance can be significantly enhanced by employing techniques such as driving the SMPS mode pin high or utilizing an external 3.0V shunt reference to minimize noise and offset [61].

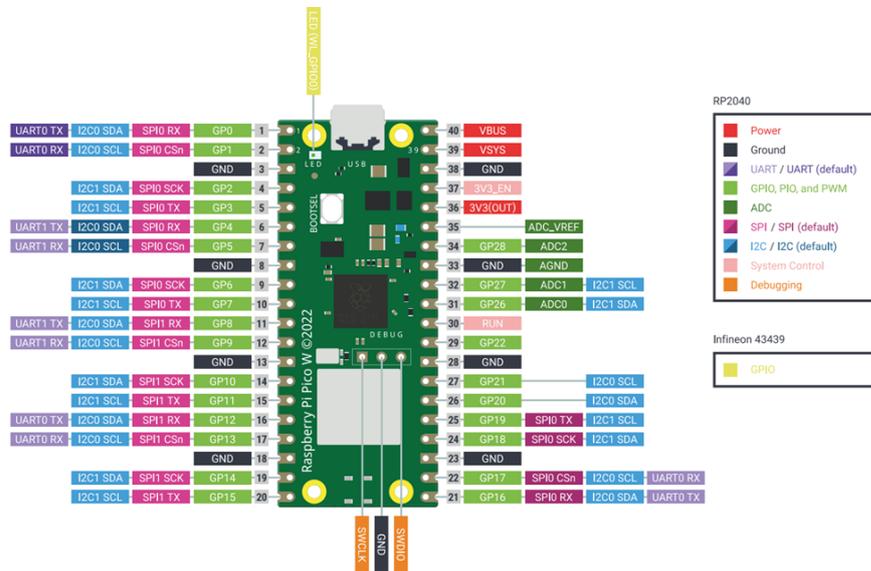
In addition to the ADC, the Pico W includes integrated Wi-Fi, facilitating seamless wireless communication without the need for additional external modules. This feature enhances the system's reliability and reduces the complexity of the hardware design. The Wi-Fi module supports 2.4GHz wireless interfaces, making it suitable for various network configurations [61].

To further ensure the system's reliability, the Raspberry Pi Pico W incorporates a watchdog timer. This feature is essential for maintaining system stability, as it allows the system to recover from potential hang-ups during data acquisition and processing. Alongside this, circular buffering is employed to manage the continuous stream of data from the ADC efficiently. This method prevents data loss and ensures smooth and consistent data processing [61, 53].

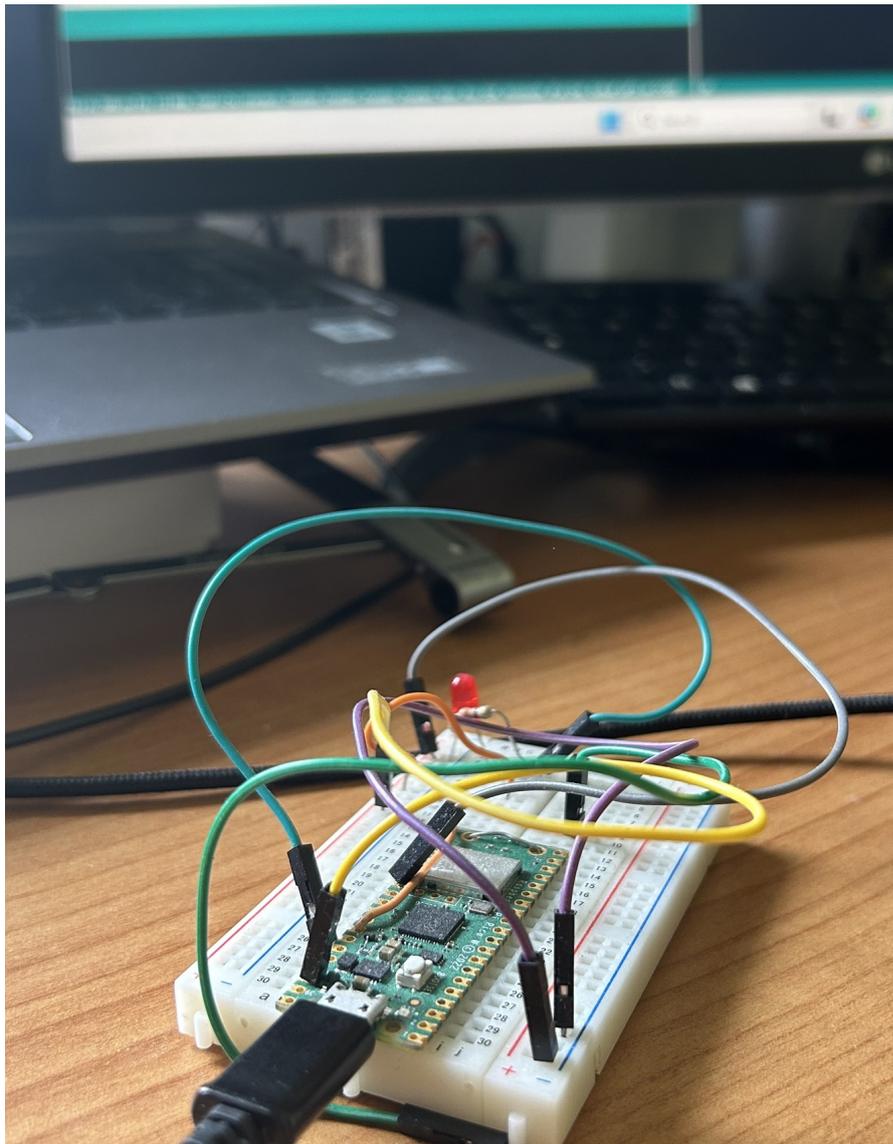
Additionally, the firmware incorporates advanced techniques to ensure data integrity and reliability, including error detection algorithms, data validation processes, and redundancy mechanisms. These methods encompass checksum verification, parity checks, and data encryption to safeguard against data corruption and unauthorized access. By implementing these techniques, the PRIMULA system not only maintains the accuracy of the collected data but also ensures its secure transmission, thereby enhancing overall system reliability.

Overall, the Raspberry Pi Pico W's amalgamation of powerful processing capabilities, integrated wireless connectivity, efficient analog-to-digital conversion, and enhanced system reliability makes it an ideal choice for the PRIMULA project. This microcontroller underpins the project's objective to develop a robust real-time monitoring solution for Parkinson's patients, ensuring both high performance and user-friendly operation.

### 3.6.2 Pinout Diagram



**Figure 3.2:** This diagram illustrates the layout of the GPIO pins, highlighting their various functions including power, ground, UART, SPI, I2C, PWM, ADC, and system control, providing a detailed reference for the hardware setup.



**Figure 3.3:** Real-world setup of the Raspberry Pi Pico W.

## 3.7 Software Components

### 3.7.1 Arduino IDE

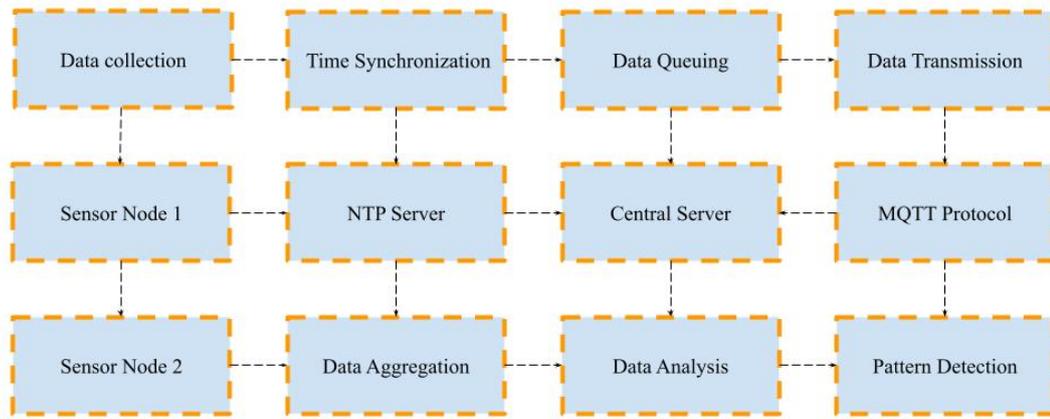
The development environment for the PRIMULA firmware is the Arduino Integrated Development Environment (IDE). This is selected for its user-friendly interface, extensive library support, and compatibility with the Raspberry Pi Pico W microcontroller. This selection provides the developer with access to a vast

repository of pre-built functions and examples.

The firmware is authored in C/C++, leveraging the rich array of libraries available within this ecosystem. The utilization of these libraries streamlines the implementation of advanced features such as Wi-Fi communication, MQTT data transmission, and time synchronization using NTP. Moreover, the modular nature of the Arduino IDE allows for scalable and maintainable code development, which is essential for the evolving needs of the PRIMULA system.

### 3.8 Data Flow in PRIMULA

For the sake of understanding how data moves through the system, Figure 3.4 outlines the sequential stages from data collection to pattern detection.



WorkFlow of PRIMULA

**Figure 3.4:** Data flow in PRIMULA from data collection to pattern detection.

The PRIMULA system’s architecture for handling data is carefully designed to facilitate the process of gathering, aligning, and transmitting motion data from multiple IMUs distributed across different sensor nodes, referred to as "Sensor Node 1" and "Sensor Node 2."

The process begins with each sensor node recording movements that mimic the physical manifestations of PD symptoms, while simultaneously timestamping each data point using NTP. The synchronization function uses a method that gradually increases the interval between retries when there are issues, aiming to avoid network overload and maintain timing accuracy, which is crucial for correct data correlation.

After synchronization, the motion data from each sensor node is temporarily stored in separate circular buffers. These buffers are designed to manage continuous data flows and prevent data loss during transmission. Concurrently, the system

employs duty cycling techniques, which allow the sensor nodes to alternate between active and low-power states to conserve energy without compromising data collection.

The motion data is then transmitted via the Raspberry Pi Pico W's built-in Wi-Fi modules, utilizing the MQTT protocol to ensure reliable message delivery. This setup is reinforced by mechanisms to prevent duplicate messages and robust recovery strategies to maintain data flow even in dynamic network conditions. Upon reaching the central server, the data is aggregated and synchronized using accurate timestamps provided by the NTP server, enabling real-time analysis and continuous monitoring.

To ensure system performance and reliability, the software records metrics such as the number of successfully transmitted MQTT messages, NTP synchronization attempts, and failures. These metrics provide concrete evidence of the system's operational effectiveness. Additionally, an inactivity detection system continuously monitors the system's status, ensuring the system remains connected and addressing any issues that may cause downtime. The software also includes comprehensive logging and debugging features, allowing detailed real-time inspection of the system's operation and stability over time.

Moreover, a button press simulation feature within the `collectAndQueueReadings()` function has been added, enabling automated tests of the data collection process to ensure the system works consistently without requiring manual operation.

In summary, the methodologies implemented in PRIMULA from precise time synchronization using exponential backoff, reliable MQTT communication with QoS Level 0 and 1, to validation metrics and testing establish a robust foundation for accurate, dependable, and efficient real-time monitoring of PD disease symptoms. This data flow architecture not only ensures reliable system performance but also paves the way for future expansion and the integration of advanced pattern detection algorithms.

## Chapter 4

# Implementation Prototype

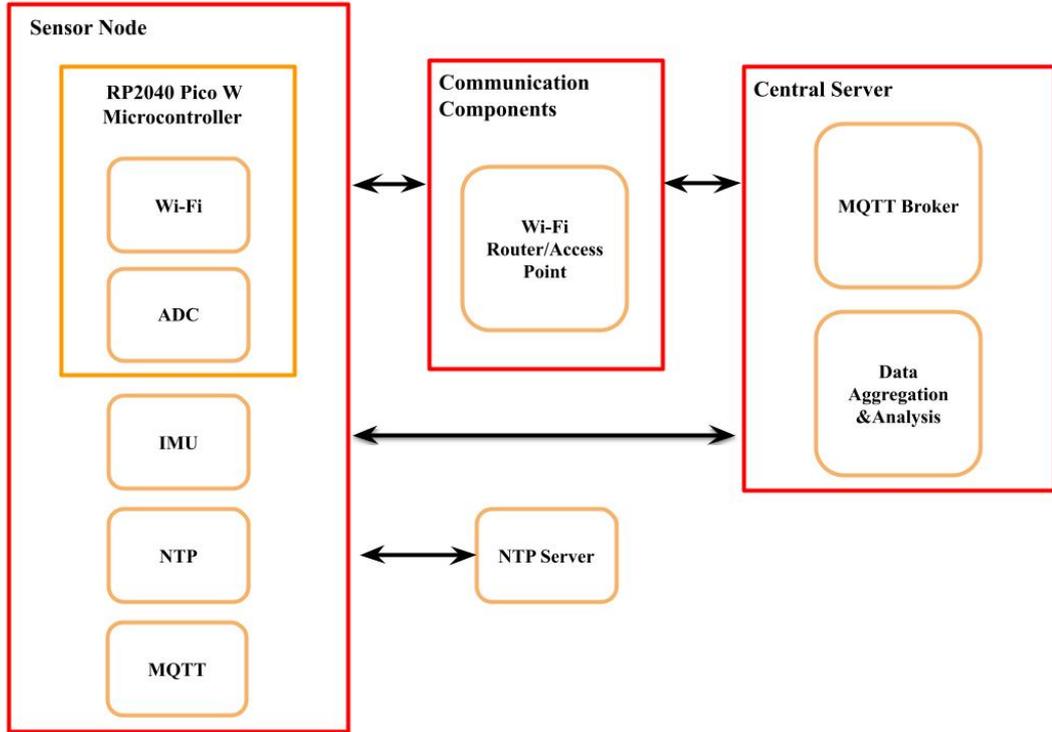
This chapter details the practical implementation of the PRIMULA system, transitioning from conceptual design to a functional prototype. It encompasses system design and architecture, firmware development, comprehensive testing and validation, and concludes with insights and future enhancements.

### 4.1 System Design and Architecture

In this project designed specified for using a single-node setup and choosing components that fit its goals, which is designed with a modular approach to facilitate scalability, flexibility, and ease of integration for future work with additional sensors and functionalities. The system's modular design ensures precise data collection, synchronization, and transmission, addressing the critical challenges of real-time monitoring in our scenario.

Figure 4.1 shows the conceptual architecture of the PRIMULA system.

### Conceptual Framework of the PRIMULA System



**Figure 4.1:** Conceptual architecture of the PRIMULA system.

#### 4.1.1 Addressing Design Challenges

This subsection delves into the primary challenges encountered during the design phase and the methodologies employed to address them effectively.

##### Ensuring Precise Time Synchronization

Accurate time synchronization is crucial for correlating sensor data with real-world events, enabling meaningful analysis of PD symptoms. One of the primary challenges was maintaining precise synchronization with NTP server, particularly in environments with unstable network conditions.

To address this, the firmware integrates an *exponential backoff retry mechanism*, which progressively increases the delay between successive synchronization attempts following each failure. This strategy helps alleviate network congestion and improves the likelihood of successful synchronization. Additionally, during the prototype phase, a local NTP server is utilized to reduce latency and improve synchronization

accuracy, further ensuring precise data correlation.

### **Reliable Data Transmission**

Ensuring data integrity and timely transmission is critical for making the collected physiological data available for analysis without loss or delay. The implementation of the MQTT protocol with QoS level 1 was strategically chosen to balance reliability and network efficiency.

Maintaining a stable connection to the MQTT broker, however, presented challenges, particularly in environments with intermittent network connectivity. To address these issues, the firmware includes robust error-handling mechanisms and automatic reconnection strategies. These mechanisms monitor the connection status and automatically initiate reconnection attempts upon detecting disconnections, ensuring continuous data transmission without requiring manual intervention.

### **Power Efficiency in PRIMULA System**

The PRIMULA system, designed for prolonged use in medical monitoring, emphasizes power efficiency. This was achieved through optimized code, minimizing active processing time and putting the system into low-power sleep modes when idle. The Raspberry Pi Pico W was chosen specifically for its low power consumption. Additionally, memory was managed efficiently by employing appropriate data structures and avoiding excessive dynamic memory allocation, ensuring the system operates smoothly without unnecessary power use.

### **Scalability and Future Expansion**

In fact, the modular design of the PRIMULA system was pivotal in addressing scalability challenges. By structuring the system in a modular manner, future expansions—such as integrating additional sensors or incorporating advanced data processing algorithms—can be implemented without significantly impacting the system’s existing functionalities. This approach simplifies the introduction of new features and enhances the system’s adaptability, ensuring that it can meet our scenario.

#### **4.1.2 Flowchart**

The operational framework of the PRIMULA system is depicted in the flowchart in Figure 4.2. This system is meticulously designed to collect and transmit time-synchronized measurements using NTP and MQTT protocols, ensuring precise timing and efficient data handling, which are critical components for real-time applications.

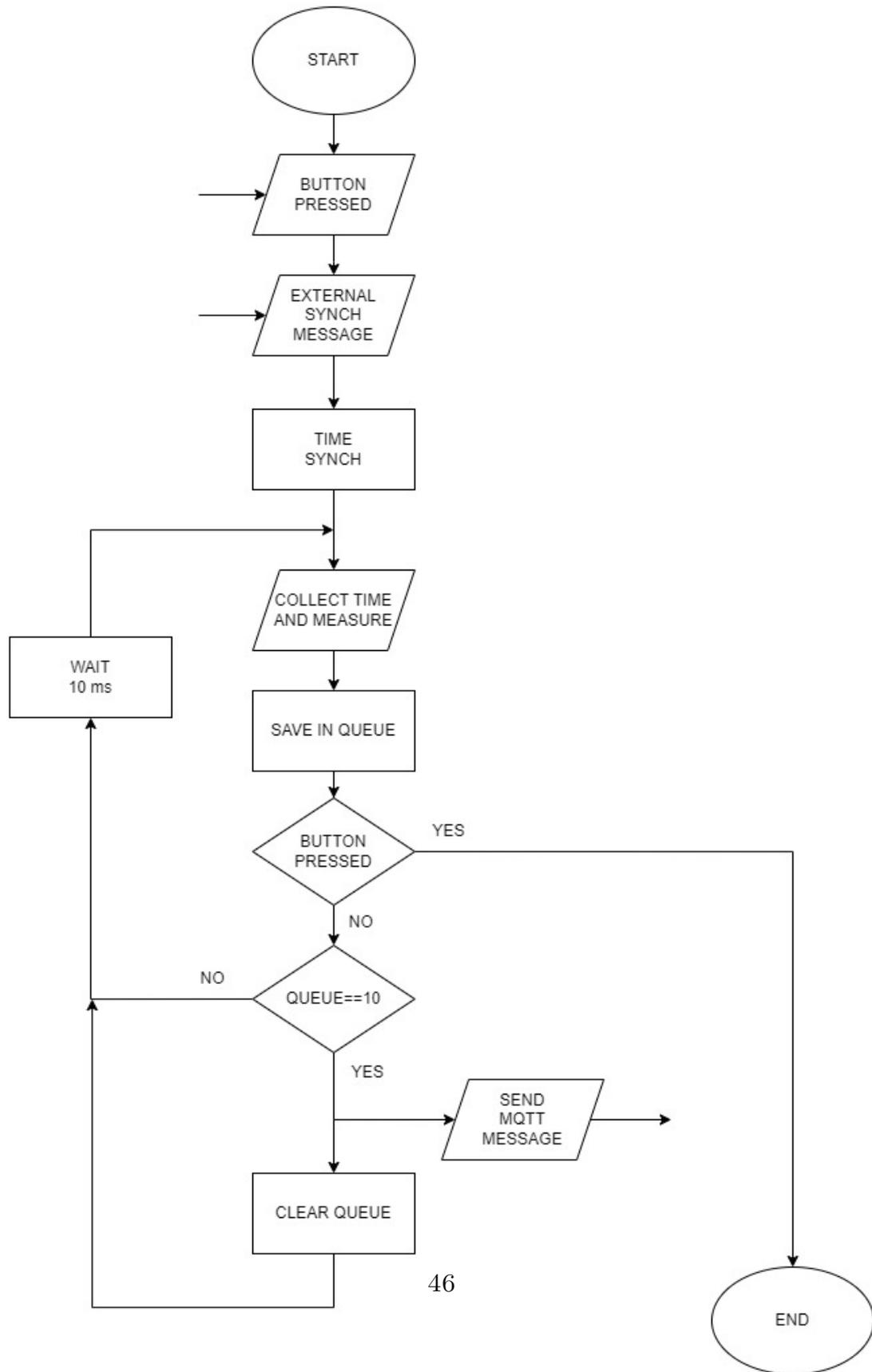


Figure 4.2: Flowchart of the PRIMULA system's operational framework.

## **Process Initiation and Data Collection**

The initiation of the process commences upon the activation of the system. The activation of a button initiates the data collection phase, during which an external synchronization message is received. This message initiates the time synchronization process through NTP. For the purpose of this prototype, a local laptop is designated as the NTP server, guaranteeing a balance between reasonable accuracy in timekeeping and the avoidance of excessive precision.

## **Measurement and Data Queuing**

Post-synchronization, the system collects the current time alongside the necessary measurements, subsequently storing this data in a queue. This queuing mechanism facilitates organized data handling, preparing the system for conditional data transmission.

## **Conditional Data Transmission**

The system employs a dual-condition approach for data transmission. Firstly, data can be transmitted immediately upon a subsequent button press. Secondly, data is transmitted in batches when the queue accumulates ten data points. In either case, the data is encapsulated in an MQTT message and transmitted to the designated MQTT broker, ensuring reliable and efficient data delivery. After transmission, the queue is cleared, allowing for continuous data monitoring and collection.

## **System Continuity**

This process operates in a loop, continuously monitoring for button presses and queue thresholds, thereby maintaining an uninterrupted data collection and transmission cycle until manual termination is initiated.

# **4.2 Firmware Development**

The firmware is the heart of the PRIMULA system, managing everything from collecting data to sending it.

## **4.2.1 Firmware Development Objectives**

The firmware was carefully designed to meet four main goals: making sure it works closely with NTP server to accurately time sensor data, creating strong and effective ways to send data to the MQTT broker to reduce errors and loss, using resources wisely to save power and make the microcontroller work better, and keeping the

system fast and reliable when responding to user needs and events. These goals together make the firmware reliable, efficient, and able to handle the demands of real-time monitoring PD symptoms.

## 4.2.2 Libraries Dependency

However, for developing firmware, it is essential to clearly understand the libraries and dependencies between them to facilitate the implementation. These libraries provide essential functionality, which is standardized and reliable through community or industry testing. Another aspect is the simplification of complex functions to empower coding procedures and performance.

All of these libraries are compatible with the Raspberry Pi Pico W and Arduino IDE, making them straightforward for integration.

- **WiFi.h**: Facilitates Wi-Fi connectivity, enabling communication with the network and transmission of data to the central server. This library provides essential functionality for establishing and managing Wi-Fi connections. However, it can be power-intensive, which is a consideration for battery-operated systems.
- **WiFiUdp.h**: Handles UDP communication and is crucial for NTP implementation. It is lightweight and well-suited for high-speed data transmission [62]. While UDP lacks error correction and flow control mechanisms, its usage is efficient for NTP because it doesn't require the overhead of establishing a connection, as with TCP. NTP packets are small and need to be sent quickly and frequently; therefore, UDP is more efficient than TCP for this application [54, 63].
- **time.h**: Used for tasks like obtaining the current time and calculating average timings. While this library lacks a RTC, time-related functions are effectively managed by interfacing with the NTP server to obtain real-time data.
- **PubSubClient.h**: Utilized to implement MQTT communication by leveraging a lightweight and efficient publish/subscribe model, which is ideal for our application. The advantage is reliable data transmission between nodes and improved cloud processing, despite potential memory constraints and network connectivity handling. To maximize the potential of this protocol, buffer sizes were adjusted, and error-handling mechanisms were implemented to address limitations and ensure reliable real-time data transmission in PRIMULA.

### 4.2.3 Key Functionalities

**Table 4.1:** Key Functionalities of the PRIMULA Firmware

Functionality	Description	Implementation/Method
Time Synchronization	Ensures accurate timestamping of sensor data, enabling precise correlation with PD symptom events.	Utilizes the <code>synchronize_time()</code> function, which leverages NTP to align the system's clock with a reference time source.
Data Acquisition	Efficiently collects physiological data via the ADC interface, ensuring high-resolution and consistent sensor readings.	Managed by the <code>collectAndQueueReadings()</code> function, which interfaces with the ADC to obtain sensor readings averaging approximately 24.29 $\mu$ s.
Data Transmission	Maintains data integrity and reliability by ensuring each message is delivered at least once, crucial for accurate monitoring.	Facilitated by the <code>sendMQTTMessage()</code> function, which constructs and publishes data packets to the MQTT broker using QoS level 1.
Performance Logging	Tracks and logs key metrics to enable performance analysis and validate system reliability and efficiency.	Implements counters for total messages sent, failed transmissions, NTP attempts, and failures, providing valuable data for system assessment.
Error Handling	Detects failures, initiates retries with exponential backoff, and logs pertinent information to ensure graceful recovery from transient issues.	Integrated throughout the firmware, particularly in network connectivity and data transmission processes, to manage and mitigate errors without manual intervention.
System Responsiveness	Maintains prompt responsiveness to user interactions and system events, ensuring seamless and uninterrupted operation.	Achieved by optimizing the main loop for minimal delays and implementing interrupt-driven processing where necessary.

### 4.2.4 Function Definitions

The main features of the firmware are described in this subsection along with their roles and how they work together in the system.

### **setup\_wifi()**

The function `setup_wifi()` is responsible for establishing and maintaining a stable Wi-Fi connection. It incorporates retry logic to handle initial connection failures and initializes the Wi-Fi module using the provided SSID and password. By ensuring the system's continuous network connectivity, this feature enables constant communication between the MQTT broker and the NTP server.

### **reconnect\_mqtt()**

The `reconnect_mqtt()` function ensures that the MQTT client maintains a stable connection to the broker. If a disconnection occurs, the function applies a reconnection strategy that incorporates exponential backoff. As result, this approach avoids rapid, repeated reconnection attempts, which could otherwise congest the network or overload the broker.

### **synchronize\_time()**

At the core of the system's time synchronization capability is the `synchronize_time()` function. While this function manages communication with the NTP server by constructing and transmitting NTP request packets, processing the server's responses, and updating the system's epoch time accordingly. It incorporates robust error-handling and retry strategies to ensure consistent, precise, and reliable timekeeping.

### **sendMQTTMessage()**

Despite the fact, `sendMQTTMessage()` function is responsible for creating and publishing MQTT messages that contain timestamped sensor data. Hence, data is formatted into a structured JSON, facilitating compatibility and efficient parsing by the recipient system. Additionally, the function tracks and logs the success of each message transmission, collecting valuable metrics for future performance analysis.

### **callback()**

The `callback()` function is responsible for handling incoming MQTT messages on subscribed topics. While the current implementation may not require intricate message processing, this function lays the groundwork for future extensions, where the system might need to handle incoming commands or configuration updates.

### **timerCheck()**

The `timerCheck()` function is designed to monitor system inactivity and manage essential housekeeping tasks. By keeping track of the elapsed time since the last activity, it can trigger low-power modes or initiate system resets in the event of prolonged inactivity. This contributes to enhanced power efficiency and improved system reliability.

### **collectAndQueueReadings()**

this function is used to manages the data acquisition process. In fact, It simulates user interactions, triggers sensor readings, synchronizes time, and queues the collected data for subsequent transmission. Inorder to ensures that data collection and transmission occur in a structured, efficient, and timely manner, maintaining the system's responsiveness and overall operational efficiency.

## **4.2.5 Techniques Used in the Firmware Code**

This framework employed several advanced techniques to meet the outlined objectives of reliability, efficiency, and responsiveness. This subsection provides an in-depth analysis of these techniques, explaining their implementation within the code and their impact on system performance. A detailed summary of these integration techniques is provided in Table 4.2.

**Table 4.2:** Integration of Techniques for Optimal Performance

<b>Integration Aspect</b>	<b>Description</b>	<b>Impact</b>
Synergistic Interaction of Components	Combines distinct firmware techniques to provide cohesive and resilient operation.	Reduces network congestion and increases synchronization success rates
Balancing Reliability and Efficiency	Harmonizes MQTT's QoS level 1 with robust error handling to ensure reliable data transmission without excessive network overhead.	Maintains data integrity and optimizes network usage
Optimizing Resource Utilization	Integrates power management and memory optimization techniques to maximize the efficiency of the microcontroller's limited resources.	Conserves energy and ensures stable, long-term operation
Enhanced System Responsiveness	Implements optimized main loops and interrupt-driven processing to ensure swift responses to user interactions and system events.	Ensures seamless and uninterrupted real-time monitoring
Scalability and Future-Proofing	Designs firmware architecture to be modular and adaptable, facilitating the integration of additional sensors and advanced features.	Enables easy expansion and integration of complex data analytics

The integration of advanced firmware techniques is pivotal to the PRIMULA system's performance, as elucidated in Section 4.2.5. These integrated approaches ensure that the system remains reliable, efficient, and responsive, thereby enhancing its capability to monitor Parkinson's Disease symptoms in real-time.

### 4.2.6 Challenges Encountered and Solutions

The firmware development phase of the PRIMULA system confronted several critical challenges, as elucidated in Section 4.2.6. Through the implementation of advanced retry mechanisms, robust data transmission protocols, and strategic resource management, these challenges were effectively surmounted, ensuring the system's reliability and efficiency.

## 4.3 Test and Validation

A systematic testing and validation protocol was executed to evaluate the operational efficacy of the PRIMULA system. The principal objectives encompassed the verification of time synchronization precision, the accuracy of data acquisition, the reliability of data transmission mechanisms, and the overall robustness of the system architecture. The subsequent sections delineate the methodologies employed and the results obtained during these evaluative procedures.

### 4.3.1 Time Synchronization Validation

To comprehensively evaluate the time synchronization performance of the PRIMULA system, a dedicated test was conducted over a 24-hour period. During this evaluation, the system endeavored to synchronize with the NTP server every 10 seconds, resulting in a total of 8,640 synchronization events.

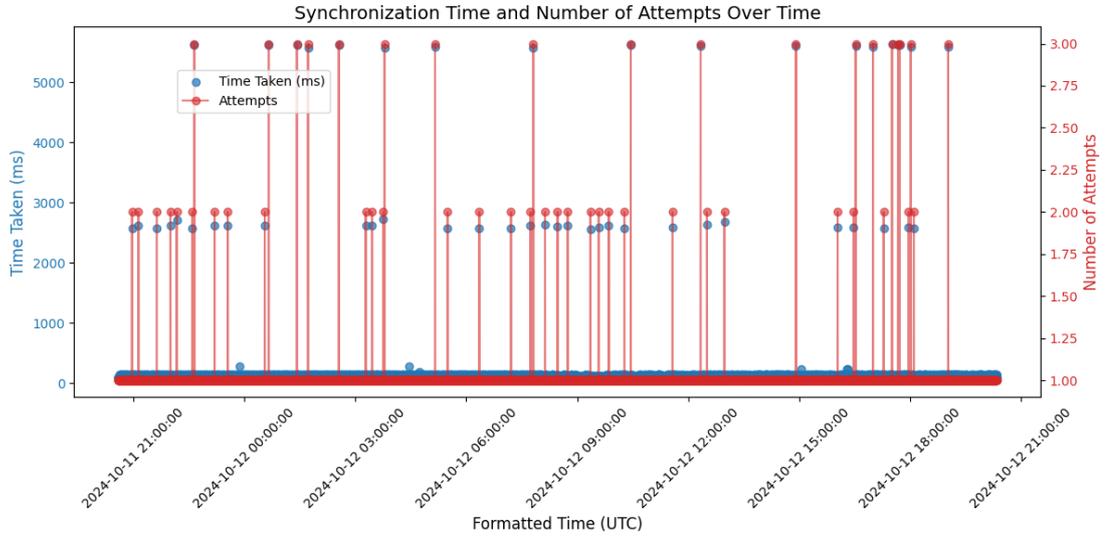
#### Results

An advanced data extraction methodology was employed to capture the number of attempts per synchronization event and the total time taken, accounting for retries necessitated by network delays or packet loss. Table 4.3 summarizes the synchronization results.

**Table 4.3:** Synchronization Statistics Over 24 Hours

Metric	Value
Total Synchronization Events	8,640
Successful Synchronizations	8,640
Average Time Taken (ms)	121.36
Maximum Time Taken (ms)	5,642
Events with 1 Attempt	8,591
Events with Multiple Attempts	49

Figure 4.3 illustrates the NTP synchronization times over 24 hours, highlighting events that required multiple synchronization attempts.



**Figure 4.3:** NTP Synchronization Times Over 24 Hours, with Markers Indicating the Number of Attempts

## Analysis and Conclusion

The synchronization data presented in Table 4.3 demonstrates an impeccable success rate, with all 8,640 synchronization attempts achieving precise alignment with the NTP server. The average synchronization latency of 121.36 milliseconds underscores the system’s capability to maintain swift and accurate timekeeping.

Notably, 8,591 events (approximately 99.44%) succeeded on the first attempt, while only 49 instances required multiple retries. This highlights the effectiveness of the implemented exponential backoff retry mechanism in addressing transient connectivity challenges.

Figure 4.3 further corroborates these findings, illustrating synchronization times predominantly clustering around the average latency, with sporadic spikes corresponding to the few multi-attempt events. This consistency in synchronization performance, even over an extended 24-hour period, underscores the robustness of the firmware’s time synchronization protocols and its resilience in maintaining temporal precision under continuous operational stress.

Consequently, the PRIMULA system exhibits exemplary time synchronization performance, characterized by flawless synchronization success rates and consistently low latency metrics. These outcomes validate the effectiveness of the NTP synchronization implementation and substantiate the system’s suitability for real-time PD monitoring within a prototype framework.

## 4.3.2 Integrated System Validation

### 4.3.3 Test Setup and Methodology

A comprehensive integrated firmware test was conducted to evaluate the PRIMULA system's performance across multiple modules operating concurrently. The test simulated real-world usage scenarios by initiating data acquisition and transmission events through simulated button presses.

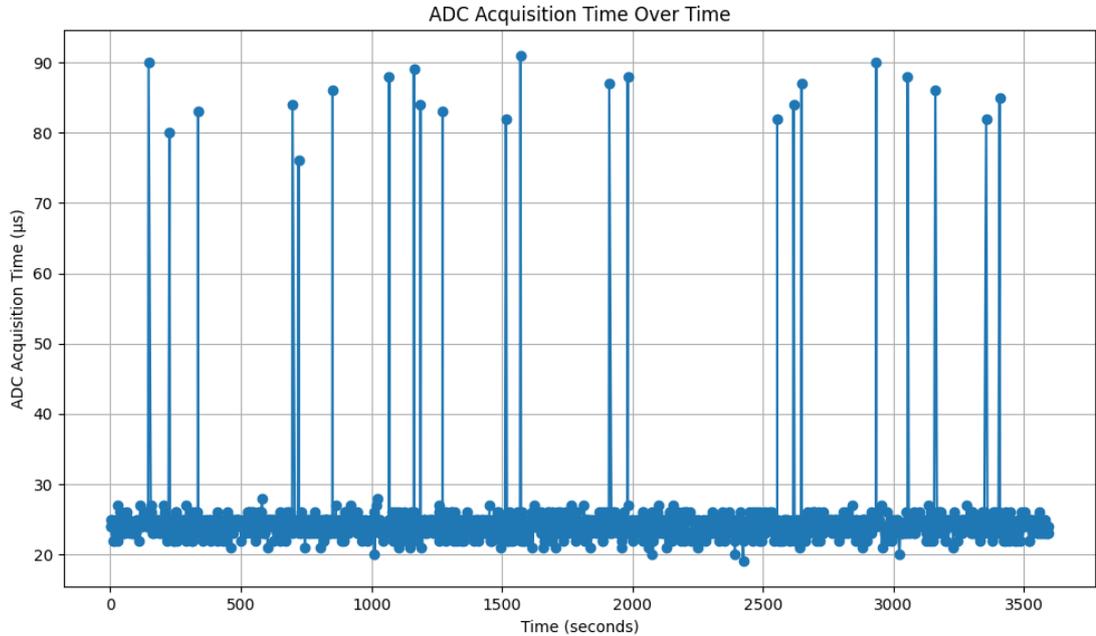
#### Simulated Button Presses

Button presses were systematically simulated at regular intervals to trigger the following sequence of operations:

1. **Data Collection:** Upon each button press, ten ADC measurements were acquired at regulated intervals.
2. **Data Processing:** The collected ADC data was displayed on the serial monitor and stored in a transmission queue.
3. **Time Synchronization:** The system synchronized its clock with the NTP server to timestamp the data batch.
4. **Data Transmission:** The ADC data, along with the timestamp, was encapsulated into MQTT messages and dispatched to the designated MQTT broker.

### 4.3.4 Data Collection and Processing Validation

#### Results and Analysis



**Figure 4.4:** ADC Acquisition Time Over 6 Hours, *Represents the ADC acquisition time during the observation period, showing consistent timing with occasional spikes due to system processing loads.*

Figure 4.4 depicts the ADC acquisition times over the test in six hours. The system maintained an average ADC acquisition time of  $24.29 \mu\text{s}$ , with individual measurements ranging between  $22 \mu\text{s}$  and  $26 \mu\text{s}$ . This consistency highlights the system's proficiency in real-time data collection, ensuring that sensor readings are captured promptly and accurately. The minimal variation in acquisition times reflects the firmware's efficiency and the reliability of the ADC interface, guaranteeing that sensor data is consistently and accurately captured for subsequent analytical processes.

### 4.3.5 Data Transmission Validation

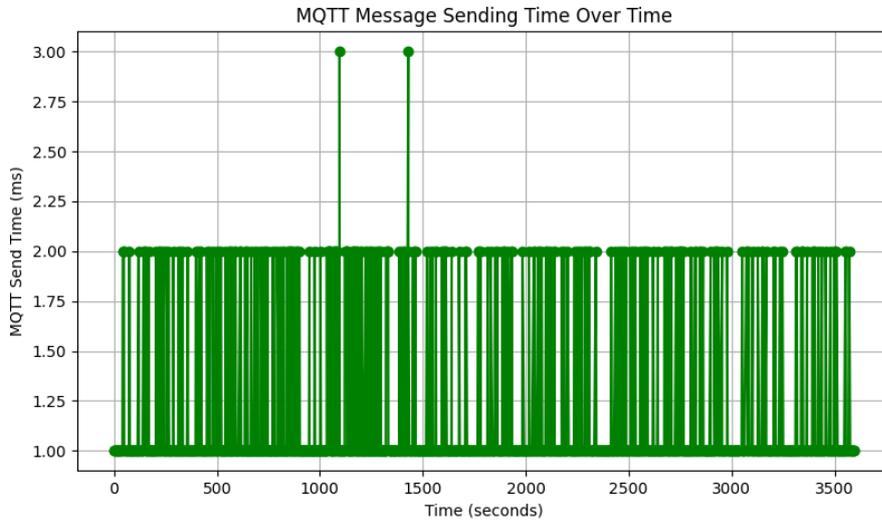
#### Results and Analysis

Table 4.4 presents the transmission metrics observed in 6 hours testing. The system achieved a 100% success rate, successfully transmitting all 1,693 MQTT messages.

The average transmission time was 1.43 ms, with the fastest transmission at 1 ms and the slowest at 2.577 ms. Notably, 1,644 events (97.1%) succeeded on the first attempt, while 49 events (2.9%) required multiple attempts, highlighting the robustness of the implemented exponential backoff retry mechanism in handling transient connectivity challenges.

**Table 4.4:** Data Transmission Statistics Over 6 Hours

Metric	Value
Total Transmission Attempts	1,693
Successful Transmissions	1,693
Failed Transmissions	0
Success Rate (%)	100%
Average Transmission Time (ms)	1.43
Maximum Transmission Time (ms)	2.577
Events with 1 Attempt	1,644
Events with Multiple Attempts	49



**Figure 4.5:** MQTT Message Transmission Times Over 6 Hours, with Markers Indicating the Number of Attempts

Figure 4.5 graphically illustrates the MQTT message transmission times , with

markers indicating the number of transmission attempts per message. The figure showcases consistently low transmission times, with occasional deviations attributable to simulated network delays or processing loads.

### 4.3.6 System Responsiveness and Reliability

#### Results and Analysis

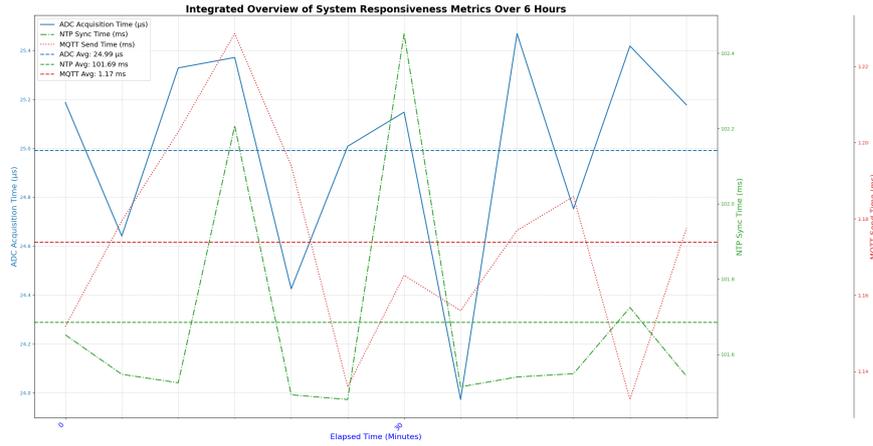


Figure 4.6: System Responsiveness Metrics Over 6 Hours

Figure 4.6 presents an aggregated visualization of key system responsiveness metrics—ADC Acquisition Time, NTP Synchronization Time, and MQTT Send Time—over a continuous "6-hour monitoring period". The figure provides a clear and concise overview of the system's performance, highlighting both individual metric trends and their respective average values.

- "ADC Acquisition Time": Averaged at "24.29 µs", with a range of "22 µs" to "26 µs".
- "NTP Synchronization Time": Averaged at "102 ms", ranging from "100 ms" to "110 ms".
- "MQTT Message Transmission Time": Averaged at "1.43 ms", with a maximum of "2.577 ms".

The integrated analysis indicates that the PRIMULA system maintains high responsiveness across all operational metrics. The consistent ADC acquisition times ensure real-time data collection, while the reliable NTP synchronization guarantees accurate timestamping of data batches. The swift MQTT message transmission

times affirm the system’s capability to deliver data promptly to the broker, essential for real-time monitoring applications.

The concurrent operation of ADC data acquisition, NTP synchronization, and MQTT message transmission underscores the PRIMULA system’s ability to handle multiple tasks efficiently without performance degradation. The high success rates and minimal latency across all metrics reflect the system’s robustness and reliability, making it well-suited for real-time PD symptom monitoring.

## 4.4 Conclusion

This thesis delineates the development and implementation of the PRIMULA system, an innovative IoT-based wearable device meticulously engineered for the real-time monitoring and management PD. Through an extensive examination of WSNs, WBANs, and sophisticated communication protocols, this research addresses critical challenges inherent in PD management, including symptom heterogeneity, limitations of conventional assessment tools, and the complexities associated with medication side effects.

The comprehensive literature review presented in Chapter 2 offers an exhaustive analysis of the foundational technologies underpinning WSNs and WBANs. It scrutinizes various network topologies, communication protocols, and optimization strategies, highlighting the imperative for cross-layer optimization and advanced routing protocols to enhance energy efficiency, data reliability, and network scalability within healthcare applications [17, 18, 13]. Building upon these insights, Chapter 3 introduces the PRIMULA project framework, emphasizing the integration of asynchronous communication via MQTT and precise time synchronization through the NTP. The system design leverages the Raspberry Pi Pico W microcontroller for its cost-effectiveness and robust capabilities, ensuring efficient data acquisition, processing, and transmission [15, 25].

Chapter 4 delves into the practical implementation of the PRIMULA system, focusing on firmware development aimed at achieving reliable time synchronization, efficient data transmission, and power optimization. Rigorous testing validates the system’s performance, demonstrating flawless synchronization rates, consistent data acquisition times, and reliable MQTT message transmissions over extended operational periods [26, 27]. These results underscore the system’s capacity to maintain precise and dependable monitoring essential for managing PD symptoms effectively.

The PRIMULA system effectively mitigates the limitations of traditional PD assessment tools by enabling continuous, objective, and real-time monitoring of both motor and non-motor symptoms [62, 5]. This capability facilitates personalized treatment plans, timely medical interventions, and enhanced patient outcomes,

thereby addressing significant gaps in current PD management practices. The integration of advanced sensors, real-time data processing, and reliable communication protocols positions PRIMULA as a transformative tool in the landscape of chronic disease management [23, 11].

## 4.5 Future Work

While the PRIMULA system demonstrates substantial advancements in real-time PD monitoring, several avenues remain open for further research and development to enhance its functionality, scalability, and clinical applicability. Integrating advanced data analytics and machine learning algorithms presents a promising direction for future work. By analyzing the aggregated data, the system can detect subtle patterns and trends in PD symptoms, facilitating predictive analytics that allow for anticipatory interventions before symptom exacerbation [22, 19]. This integration will not only enhance the precision of treatment plans but also provide personalized health insights tailored to individual patient data [20].

Expanding the system's scalability through multi-node configurations equipped with additional IMUs and diverse sensor modules will enable comprehensive monitoring of various body regions, offering a holistic view of a patient's condition [21, 54]. Developing and integrating advanced routing and data aggregation protocols will be crucial in managing the increased data flow and ensuring efficient communication between multiple sensor nodes [64, 65]. Furthermore, exploring hybrid communication protocols that combine the strengths of MQTT with other protocols such as CoAP or DDS will enhance data transmission reliability and reduce latency under diverse network conditions [1, 3]. Implementing adaptive communication strategies that dynamically switch between protocols based on real-time network performance metrics will further ensure optimal data transmission in varying environments [2].

Incorporating energy harvesting technologies, such as solar or kinetic energy harvesters, will extend the operational lifespan of wearable devices and reduce dependency on battery replacements [4, 12]. Developing sophisticated power management algorithms that dynamically adjust sensor sampling rates and transmission intervals based on usage patterns and energy availability will further enhance the system's sustainability [66]. Enhancing the user interface through the development of a user-friendly mobile application will provide patients and healthcare providers with real-time access to monitoring data, alerts, and health insights [67, 68]. Conducting extensive pilot studies and clinical trials will be essential to validate the efficacy and reliability of the PRIMULA system in real-world settings, ensuring its readiness for widespread clinical adoption [35, 69]. Ensuring compliance with relevant regulatory standards and certifications will facilitate the integration of

PRIMULA into healthcare practices, promoting its adoption as a reliable tool for PD management [33].

Strengthening data encryption protocols and implementing robust privacy measures will protect sensitive patient information from unauthorized access and cyber threats [34, 31]. Developing and integrating intrusion detection systems will monitor and respond to potential security breaches in real-time, ensuring the integrity and confidentiality of health data [32, 38].

In essence, future enhancements will focus on refining the PRIMULA system's capabilities, broadening its applicability, and ensuring its seamless integration into clinical workflows. These advancements will collectively contribute to improved quality of life for individuals living with Parkinson's Disease, underscoring the system's potential as a pivotal tool in the realm of intelligent healthcare technologies [42, 40].

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