POLITECNICO DI TORINO

Master's Degree in ELECTRONICS ENGINEERING

Master's Degree Thesis

Development of a Synchronous Sensors' Network's Firmware

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Abstract

Parkinson's Disease (PD) is a progressive neurodegenerative disorder that profoundly affects motor and non-motor functions, substantially diminishing patients' quality of life. Effective management of PD necessitates continuous and precise monitoring of symptoms to tailor personalized treatment plans and facilitate timely medical interventions. Traditional PD management approaches rely heavily on subjective clinical assessments and patient-reported outcomes, which often fail to capture the nuanced and fluctuating nature of the disease in daily activities. Advancements in Wireless Sensor Networks (WSNs) and Wireless Body Area Networks (WBANs) offer promising solutions for objective, real-time monitoring of PD symptoms. However, these technologies encounter critical challenges, particularly in ensuring data transmission reliability and maintaining precise synchronization across multiple sensor nodes, which are essential for accurate and timely data acquisition and analysis.

This thesis focuses on the development and optimization of firmware for a single-node WSN designed for PD monitoring, emphasizing synchronization accuracy and data transmission reliability. The primary objective is to enhance the firmware's capability to operate asynchronously while achieving synchronization, thereby ensuring reliable data collection and transmission. To this end, the research integrates the Network Time Protocol (NTP) for precise time synchronization and the Message Queuing Telemetry Transport (MQTT) protocol for dependable data transmission. The Raspberry Pi Pico W microcontroller is selected for its robust processing capabilities and cost-effectiveness, serving as the central processing unit of the sensor node.

A comprehensive firmware architecture was developed, incorporating features such as circular buffering and watchdog timers to ensure data integrity and system reliability. The asynchronous operation of the single-node system allows for efficient energy utilization and reduces the likelihood of data collisions. Synchronization is achieved through the implementation of NTP, which minimizes clock drift and ensures that data timestamps are accurate and consistent. MQTT, configured with Quality of Service (QoS) level 1, guarantees that messages are delivered reliably, even in environments with intermittent connectivity.

The firmware comprises several critical functions that work cohesively to maintain system performance. The `setup_wifi()` function establishes and maintains a stable Wi-Fi connection, incorporating retry logic to handle initial connection failures and ensuring continuous network connectivity essential for constant communication with the MQTT broker and NTP server. The `reconnect_mqtt()` function ensures the MQTT client maintains a stable connection to the broker, employing an exponential backoff strategy to prevent network congestion and broker overload during reconnection attempts. Central to the system's time synchronization capability is the `synchronize_time()` function, which manages communication with the NTP server, constructs and transmits NTP request packets, processes server responses, and updates the

system's epoch time with robust error-handling and retry strategies to ensure consistent and precise timekeeping.

Data transmission is managed by the `sendMQTTMessage()` function, responsible for creating and publishing MQTT messages containing timestamped sensor data formatted into structured JSON. This facilitates compatibility and efficient parsing by recipient systems while tracking and logging each message's transmission success for future performance analysis. The `callback()` function handles incoming MQTT messages on subscribed topics, laying the groundwork for future system extensions to manage incoming commands or configuration updates. Additionally, the `timerCheck()` function monitors system inactivity, managing essential housekeeping tasks such as triggering low-power modes or initiating system resets during prolonged inactivity to enhance power efficiency and system reliability. The `collectAndQueueReadings()` function manages the data acquisition process, simulating user interactions, triggering sensor readings, synchronizing time, and queuing collected data for subsequent transmission, thereby maintaining system responsiveness and operational efficiency.

Advanced techniques employed within the firmware framework include the synergistic interaction of components to provide cohesive and resilient operation, balancing reliability and efficiency by harmonizing MQTT's QoS level 1 with robust error handling to ensure reliable data transmission without excessive network overhead. Resource optimization is achieved through power management and memory optimization techniques, maximizing the microcontroller's limited resources to conserve energy and ensure stable, long-term operation. Enhanced system responsiveness is maintained through optimized main loops and interrupt-driven processing, ensuring swift responses to user interactions and system events for seamless real-time monitoring. The firmware architecture is designed to be modular and adaptable, facilitating scalability and future-proofing by enabling the integration of additional sensors and advanced features, thus supporting easy expansion and complex data analytics integration.

Experimental validation was conducted in a controlled environment simulating real-world PD monitoring scenarios. Over a 24-hour continuous operation, the system maintained a 100% synchronization success rate, with an average synchronization latency of 121.36 ms. In a subsequent 6-hour operational test, the firmware successfully transmitted 1,693 MQTT messages with a 100% success rate and an average transmission latency of 1.43 ms. These results demonstrate the firmware's efficacy in maintaining synchronization accuracy and ensuring reliable data transmission under varying network conditions, including simulated interference and node mobility.

The developed firmware significantly outperforms traditional asynchronous protocols by enhancing data transmission reliability and maintaining precise synchronization without the need for constant communication overhead. These improvements underscore the effectiveness of integrating MQTT and NTP protocols in addressing the core challenges of synchronization and data reliability within single-node WBANs. The PRIMULA system, built upon this firmware architecture, not only bridges existing gaps in PD symptom monitoring but also sets a foundation for future advancements in intelligent healthcare technologies.

Practical implications of this research are substantial, offering a scalable and reliable solution for continuous PD monitoring. By ensuring precise synchronization and dependable data transmission, the PRIMULA system facilitates personalized treatment plans and timely medical interventions, ultimately contributing to improved patient outcomes and quality of life. Moreover, the modular and scalable design of the system allows for seamless integration into diverse healthcare settings, accommodating varying patient needs and expanding to include additional sensor nodes and diverse physiological parameters.

Acknowledgment of Limitations and Future Directions

While the PRIMULA system demonstrates significant advancements in real-time PD monitoring, it is important to recognize the limitations inherent in the current setup. The firmware development and testing were conducted using a single-node configuration, which restricts the assessment of scalability and the system's performance in multi-node environments essential for comprehensive PD monitoring. Additionally, the reliance on a local NTP server, such as a laptop, introduces potential latency and single points of failure, which could adversely affect synchronization accuracy in larger deployments. The testing was performed in controlled environments, which may not fully capture the challenges posed by real-world settings, including varied interference levels and diverse user movements.

Future research will focus on overcoming these limitations by expanding the system to support multiple sensor nodes equipped with additional IMUs and diverse sensors, thereby enabling comprehensive monitoring of various body regions and providing a holistic view of a patient's condition. Incorporating energy harvesting technologies, such as solar or kinetic energy harvesters, will extend device longevity and reduce dependency on battery replacements, enhancing the system's sustainability and practicality for long-term use. Advanced data analytics, including machine learning algorithms for predictive monitoring, will be integrated to detect subtle patterns and trends in PD symptoms, facilitating anticipatory interventions and personalized health insights.

Exploring hybrid communication protocols that combine MQTT with CoAP or DDS will further enhance data transmission reliability and reduce latency under diverse network conditions, ensuring optimal performance across different deployment scenarios. Implementing adaptive communication strategies that dynamically switch between communication protocols based on real-time network performance metrics will ensure optimal data transmission in varying environments. Additionally, 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, improving user engagement and system usability.

Conducting extensive pilot studies and clinical trials will validate the system's efficacy and reliability in real-world settings, ensuring its readiness for widespread clinical adoption. Ensuring compliance with relevant regulatory standards and certifications will facilitate the integration of PRIMULA into healthcare practices. Strengthening data encryption protocols and implementing robust privacy measures will protect sensitive patient information from unauthorized access and cyber threats. 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.

Assessing the system's performance with an increased number of sensor nodes will provide insights into scalability and help identify potential bottlenecks or areas for optimization in larger network deployments. Facilitating seamless integration with existing Electronic Health Records (EHR) systems will enhance the utility of the PRIMULA system, enabling comprehensive patient data management and facilitating data-driven decision-making in clinical settings.

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.