Low-Latency EEG Marker Integration in Serious Games for Neurocognitive Assessment

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2025

"The concern for man and his destiny must always be the primary interest of any technical effort. Never forget this between your diagrams and equations"

Albert Einstein

"Believe you can, and you are halfway there."

Theodore Roosevelt

Declaración

Me permito afirmar que he realizado esta tesis de manera autónoma y con la única ayuda de los medios permitidos. Todos los pasajes que se han tomado de manera textual o figurativa de textos publicados y no publicados, los he reconocido en el presente trabajo. Ninguna parte del presente trabajo se ha empleado en ningún otro tipo de tesis.

Manizales, 2025

Julian Andres Salazar Parias

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1 Preliminaries

1.1 Motivation

Brain–Computer Interfaces (BCIs) have emerged as a powerful class of technologies that enable direct communication between the brain and external devices. These systems are increasingly being applied in neurorehabilitation, education, and clinical diagnosis due to their ability to monitor and interpret neural activity in real time. BCIs have the potential to revolutionize the way cognitive states are assessed and modulated by offering closed-loop interaction mechanisms that adapt to the user's brain dynamics [**?**, **?**]. Central to this capability is the choice of neuroimaging modality, which must meet strict criteria in temporal resolution, portability, and cost-effectiveness—especially in applications involving children or naturalistic settings.

Several neuroimaging techniques have been explored for use in Brain–Computer Interface (BCI) systems, each with distinct advantages and limitations. Functional Magnetic Resonance Imaging (fMRI) offers high spatial resolution and whole-brain coverage, but its cost, immobility, and dependence on specialized facilities make it impractical for real-time interaction or integration with everyday environments [**?**]. Magnetoencephalography (MEG) provides excellent spatiotemporal resolution but is similarly constrained by high operational costs and the need for magnetically shielded rooms [**?**]. Functional Near-Infrared Spectroscopy (fNIRS), a more portable option, measures cortical hemodynamic responses with moderate spatial resolution and tolerance to movement [**?**]. However, its low temporal resolution limits its ability to capture fast-changing neural dynamics, such as those required for attentional monitoring or neurofeedback.

Electroencephalography (EEG), by contrast, emerges as the most suitable modality for BCI applications that demand real-time responsiveness, portability, and affordability. EEG records the brain's electrical activity through non-invasive scalp electrodes, offering millisecond-level temporal resolution ideal for tracking rapid cognitive events like attention shifts or inhibitory control. While EEG's spatial resolution is lower compared to fMRI or MEG, advances in signal processing—such as QEEG, functional connectivity analysis, and source localization—have greatly enhanced its ability to extract meaningful neurophysiological markers [**?**, **?**, **?**].

Moreover, EEG's lightweight hardware, low infrastructure requirements, and compatibility with embedded systems make it an ideal foundation for interactive, portable, and scalable BCI solutions.

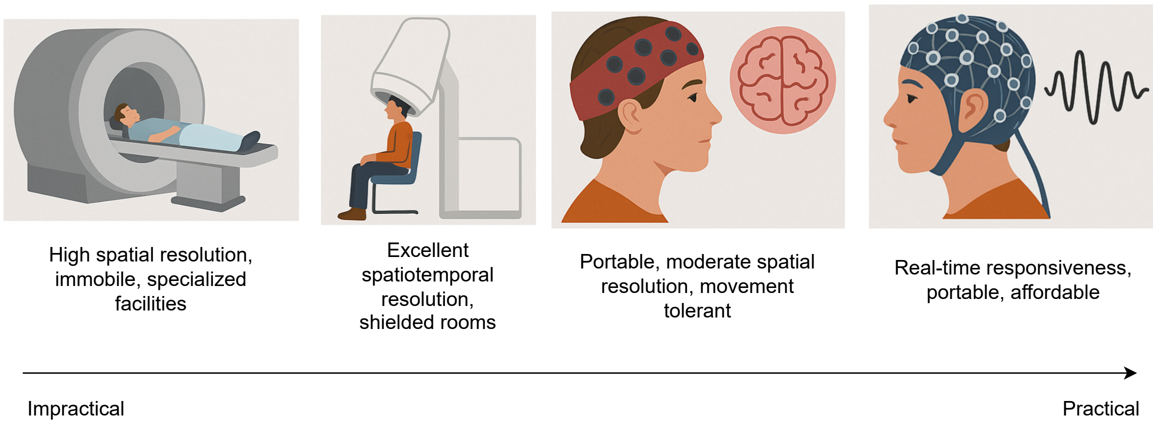

Figure 1-1: Comparison of neuroimaging modalities by spatial resolution, temporal resolution, and cost. EEG stands out for its affordability, portability, and millisecond-level responsiveness.

One of the most compelling clinical applications of EEG-based BCIs is in the assessment and intervention of neurodevelopmental disorders such as Attention Deficit Hyperactivity Disorder (ADHD). ADHD affects approximately 10 % of children in Colombia [?, ?] and is characterized by persistent symptoms of inattention, hyperactivity, and impulsivity that interfere with academic performance, social relationships, and emotional regulation. Conventional diagnostic practices rely heavily on behavioral questionnaires and clinical observation, which, while informative, are inherently subjective and susceptible to bias [?]. In this context, EEG offers a valuable alternative by enabling the objective measurement of neural correlates linked to attention and impulse control. Well-established EEG biomarkers such as elevated theta/beta ratios and altered event-related potentials (e.g., P300) have been extensively validated in the ADHD literature, making EEG a scientifically robust and clinically relevant tool for real-time cognitive monitoring and neurofeedback interventions.

Serious games are digital environments designed not solely for entertainment, but to fulfill educational, therapeutic, or cognitive objectives. In the context of neurodevelopmental disorders such as ADHD, they have become increasingly relevant as tools for both cognitive assessment and intervention [?]. Their engaging and adaptive nature allows them to target specific executive functions—like attention, inhibition, and working memory—while maintaining high user motivation, particularly among children [?]. These features make serious games particularly compatible with EEG-based BCIs for interactive cognitive modulation.

Serious games designed for ADHD not only provide engaging environments for cognitive stimulation, but also serve as structured frameworks for assessing and training specific executive functions. Two principal paradigms guide the design of these games. The first is the task-based paradigm, which integrates classical neuropsychological tasks—such as the

Go/No-Go, n-back, or Stroop test—into interactive game mechanics. This allows for the precise measurement of behavioral responses tied to well-established cognitive models [?]. The second is the neurofeedback paradigm, in which the game dynamically responds to real-time EEG signals, offering auditory or visual feedback based on the user's brain state. This paradigm supports operant conditioning mechanisms, encouraging users to self-regulate neural activity linked to attentional control and inhibition [?].

These paradigms are often aligned with four core cognitive models critical to ADHD pathology: attention, working memory, inhibition, and planning. Games targeting the attentional model aim to improve sustained and selective attention, often requiring players to maintain focus amid distractions or shifting stimuli [?]. Working memory is typically trained through tasks that require the temporary storage and manipulation of information, such as remembering sequences or updating mental representations. The inhibition model involves suppressing prepotent responses or resisting distractions—commonly implemented through fast-paced decision-making challenges or impulse control mechanics [?, ?]. Finally, the planning model emphasizes goal-directed behavior, encouraging users to sequence actions, solve multi-step problems, or anticipate future outcomes [?]. By aligning game mechanics with these cognitive models, serious games become powerful tools not only for engagement but for targeted neurocognitive intervention, particularly when combined with EEG-based BCIs that provide objective feedback on brain performance in real time.

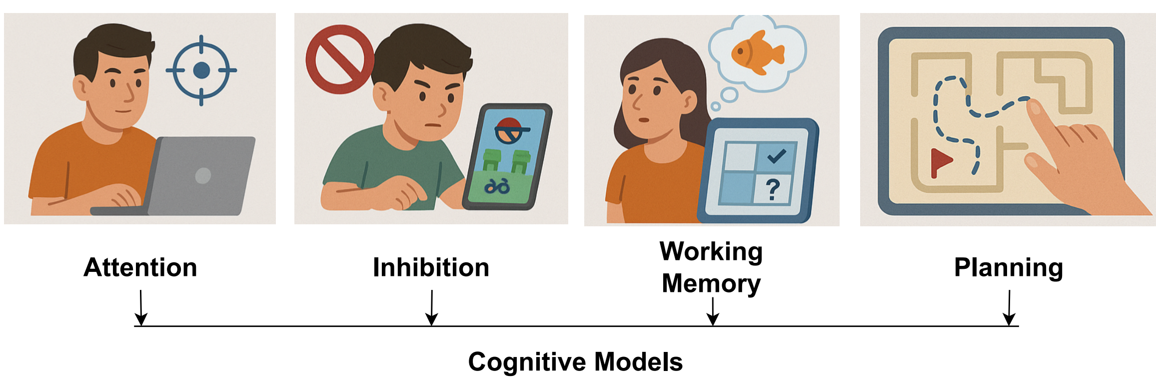

Figure 1-2: Core cognitive models targeted by serious games in ADHD interventions: attention, working memory, inhibition, and planning. Each model maps to a specific set of game dynamics and EEG markers.

Serious games integrated with BCI technology have demonstrated therapeutic benefits by reinforcing executive function, improving behavioral outcomes, and reducing symptom severity through active attention training and neurofeedback mechanisms [?]. Active BCIs, in which users intentionally modulate their focus to influence the outcome of the game, have been shown to strengthen cognitive control and promote long-term neuroplastic changes relevant to ADHD pathology [?]. These platforms also enable adaptive feedback, allowing interventions to dynamically adjust to each child's neurocognitive profile.

However, the effectiveness of such systems depends on precise temporal synchronization between game-generated stimuli and EEG signals. Detecting event-related potentials (such as the P300 wave) or dynamic oscillations in the theta and beta frequency bands during attentional tasks requires sub-millisecond timing accuracy [?, ?]. Without rigorous synchronization—typically achieved via TTL triggers or low-latency USB/Wi-Fi communication—EEG signal interpretation is susceptible to noise, jitter, and event misclassification [?]. This challenge is particularly critical in real-time therapeutic environments where accurate feedback is essential.

Recent developments in portable EEG hardware have expanded the applicability of BCIs for ADHD beyond clinical settings, enabling real-time monitoring and feedback in homes, classrooms, and therapeutic environments. Low-cost, wireless EEG headsets—equipped with dry electrodes and embedded microcontrollers—have been successfully integrated into neurofeedback systems and serious games designed for children [?]. These platforms allow for real-time signal acquisition and onboard processing, supporting closed-loop interventions without reliance on external computers. Thanks to ARM-based processors and system-on-chip (SoC) designs, it is now possible to run lightweight machine learning models directly on the device for real-time EEG classification [?]. Moreover, custom head-mounted EEG systems have shown reliable tracking of the theta/beta ratio, a key biomarker for ADHD, during interactive tasks [?].

Altogether, these technological advances offer a promising foundation for rethinking ADHD diagnosis and intervention—especially in child populations. Nevertheless, critical technical challenges remain, particularly the synchronization of cognitive stimuli with neurophysiological responses in embedded systems. This challenge motivates the present research, which aims to design and implement a portable EEG acquisition and analysis system with precise synchronization to game events, enabling objective, real-time support for cognitive stimulation and diagnostic processes in children with ADHD.

1.2 Problem statement

The design and implementation of serious games synchronized with neurophysiological signals such as electroencephalography (EEG) presents a critical challenge, especially when targeting cognitive stimulation and diagnostic support in pediatric populations with Attention Deficit Hyperactivity Disorder (ADHD). The scientific validity of such applications is fundamentally dependent on the precise temporal synchronization of at least two disparate data streams: the high-temporal-resolution physiological data from the EEG system and the context-dependent event data generated by the serious game. A core technical obstacle lies in achieving this precise synchronization, a requirement that is essential for both the accuracy of event-related potential (ERP) measurements and the effectiveness of real-time interventions.1 This thesis addresses two primary facets of this challenge: the temporal inaccuracies introduced by system-level operations and the physical limitations of the hardware itself.

1.2.1 Unpredictable Latency and Jitter Between Game Events and EEG Recordings

The primary technical issue in synchronizing EEG data with serious game events is the presence of unpredictable latency and jitter.2 Latency is the delay between an event's physical occurrence (e.g., a stimulus appearing on screen) and its corresponding timestamp being recorded in the data stream. A more pernicious issue is jitter, defined as the statistical variability in that latency over time.4 While a constant latency might be correctable in post-processing, jitter introduces random, unpredictable timing errors that cannot be easily removed after data acquisition. This issue is caused by several interrelated factors: buffering delays in data pipelines, the non-deterministic scheduling of non-real-time operating systems, variability in communication protocols (such as USB, Bluetooth, or the Lab Streaming Layer), and asynchronous execution within game engines like Unity.5 These conditions lead to a lack of temporal precision, where the timestamp of an in-game event does not accurately align with the corresponding entry in the EEG data stream. This misalignment significantly compromises the quality of neurophysiological analysis. ERP components such as the P300 and N200, which are commonly used to evaluate attentional processes in ADHD, depend on millisecond-level synchronization between stimulus onset and neural response.7 When event markers are not precisely aligned due to jitter, the resulting ERP waveform becomes temporally "smeared,çausing a reduction in both amplitude and interpretability, which degrades the signal-to-noise ratio and threatens diagnostic reliability.2 This is particularly critical in pediatric populations where subtle attentional deficits are being assessed. Furthermore, in real-time systems like neurofeedback applications, where immediate feedback is essential for operant conditioning, even minor delays can disrupt the feedback loop. If the user receives auditory or visual feedback that no longer corresponds precisely to their brain state, the therapeutic effectiveness is reduced, potentially leading to user disengagement or ineffective training outcomes.2 The temporal precision required is demanding; some brain-computer interface (BCI) paradigms require accuracy within ±2 milliseconds, yet jitter introduced by a game's graphical rendering at 50 frames per second can be as high as 20 milliseconds. Recent studies have quantified these challenges. For example, Larsen et al. (2024) found that even in systems optimized with Unity and LSL, event marker delays averaged 36 milliseconds with a jitter of 5 to 6 milliseconds—well above the acceptable margin for many ERP analyses.9 Additionally, Brain Products (2024) reports that embedded platforms lacking efficient buffering and timestamping can exhibit latencies up to 100 milliseconds, particularly under high computational load.5 These delays, caused by a lack of dedicated real-time scheduling and protocol optimization, result in a substantial loss of synchronization fidelity, ultimately undermining both research validity and clinical utility.

1.2.2 Resource and power constraints in embedded EEG platforms

The second major issue stems from the computational and energy limitations of embedded and wearable EEG systems. Designed to be mobile and unobtrusive, these systems often operate on limited battery power, constrained CPU cycles, and reduced memory.11 These constraints are exacerbated when the system must simultaneously support real-time data acquisition, multichannel EEG streaming, and high-frequency event marker registration. Conventional EEG setups that rely on centralized data processing can also lead to high energy consumption and increased data transmission latency.12 These limitations make it difficult to implement low-latency communication and high-resolution timestamping. Wireless data transmission, in particular, is very power-intensive.13 Protocols such as Bluetooth and Wi-Fi—commonly used in portable EEG systems—can introduce packet retransmissions, buffering delays, and inconsistent delivery times that worsen synchronization accuracy.5 The consequences are significant. System designers are forced to lower EEG sampling rates, simplify marker handling, or accept increased delays—all of which reduce the reliability of the collected data and the interactivity of the game.14 For example, a review of wearable EEG systems found that wireless devices consistently showed worse timing stability and synchronization performance compared to wired configurations, especially when embedded resources were under heavy computational load. Brain Products (2024) corroborates these findings, warning that system performance degrades as channel count and sampling rate increase—conditions commonly required in clinical-grade EEG systems.5 This creates a fundamental trade-off: increasing signal fidelity and temporal resolution compromises system portability, while optimizing for mobility sacrifices diagnostic precision. Therefore, a critical gap exists in establishing a robust methodology to reliably synchronize multimodal data streams from EEG systems and dynamic serious games with quantifiable, millisecond-level precision, while also operating within the power and resource constraints of embedded platforms. This thesis addresses the problem of ensuring the temporal integrity of these data streams to enable scientifically valid analysis of neuro-cognitive processes during gameplay.

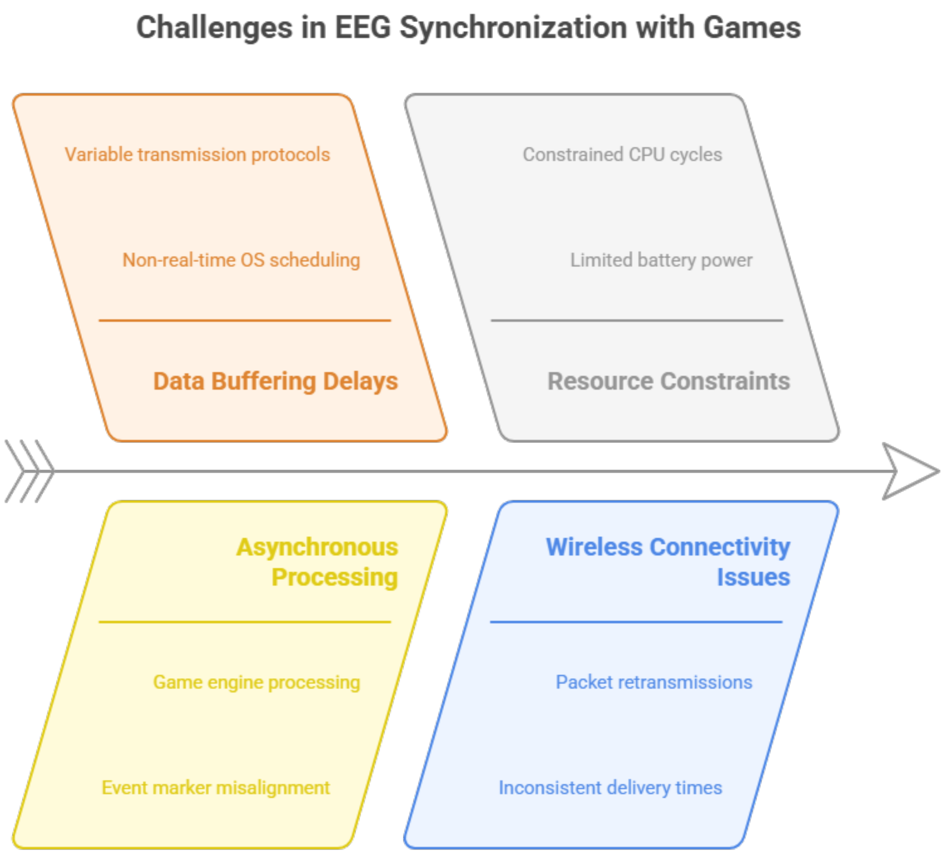
Challenges in EEG Synchronization with Games
Variable transmission protocols
Non-real-time OS scheduling
Data Buffering Delays
Constrained CPU cycles
Limited battery power
Resource Constraints
Asynchronous Processing
Game engine processing
Event marker misalignment
Wireless Connectivity Issues
Packet retransmissions
Inconsistent delivery times

Figure 1-3

1.3 Pregunta de investigación

How can a low-latency and low-jitter data synchronization framework be developed and validated to ensure the temporal integrity of multimodal data from embedded EEG systems and dynamic serious game events, while respecting the inherent resource and power constraints of such platforms?

2 Aims

2.0.1 Objetivo General

Diseñar e implementar una arquitectura de adquisición de señales EEG optimizada para aplicaciones en entornos educativos y clínicos, enfocada en la reducción de latencias y la sincronización precisa de eventos, para mejorar la evaluación objetiva de patrones cognitivos y emocionales en niños con TDAH.

2.0.2 Objetivos Específicos

1. Analizar las limitaciones técnicas de los sistemas actuales de adquisición de EEG, incluyendo las latencias de transmisión y la baja densidad de canales.
2. Desarrollar algoritmos de baja latencia y estrategias de sincronización temporal para garantizar la alineación precisa entre estímulos de juegos serios y respuestas EEG.
3. Evaluar la arquitectura propuesta en entornos clínicos y educativos, verificando su eficacia en el diagnóstico y tratamiento del TDAH.

2.1 Estado del arte

In recent years, numerous wireless systems for EEG data acquisition have been developed, with two main approaches standing out: conventional remote monitoring systems and portable smart systems. The former simply digitize the EEG signals and transmit them to a remote unit for processing, usually in a deferred manner [?]. On the other hand, portable systems preprocess the signals on a local device, such as a microcontroller (MCU), and wirelessly transmit the data using low-power consumption protocols. **2-1** This latter approach is crucial for real-time applications, where low latency is essential.

Marker synchronization in portable EEG acquisition systems [?], particularly in applications combined with serious games [?], faces several technical and operational challenges. One of the main issues lies in latency in data transmission protocols. In portable EEG systems, precise synchronization between brain events and interactions in the game is crucial [?], but inherent limitations of portable acquisition systems, such as latencies in data transfer protocols, can cause temporal mismatches. These latencies primarily stem from bandwidth constraints in wireless transmission and the need to process large volumes of data in real-time [?].

The type of electrode [?] and the number of channels [?] are determining factors in the quality of the data acquired in portable systems. Although dry electrodes offer greater portability, they tend to generate lower-quality signals due to reduced conductivity, which can complicate precise synchronization with other devices, such as serious games. On the other hand, the use of systems with **low channel density (e.g., 8-16 channels)** [?] is a common strategy in these portable systems to minimize size and improve portability. However, low channel density can affect the spatial resolution of EEG data, limiting the ability to perform accurate analysis of brain patterns. This challenge is reflected in the need to optimize sampling [?] and data transfer protocols [?] to ensure that captured signals are transmitted efficiently without significant information loss

The sampling rate is another critical factor, as it directly affects the temporal resolution of EEG signals. The combination of low channel density and insufficient sampling rate can make it difficult to capture fast brain events, such as attention shifts, which are essential in applications like serious games. Furthermore, Signal Front-End Amplifiers (AFE) [?] play a key role in signal quality. While low-cost AFEs may be suitable for portable systems, they tend to have limitations in processing capacity, which impacts data synchronization by generating noise and distortions in the EEG signals, especially when connected to mobile devices with lower processing power.

Battery life [?] is a significant constraint for portable systems that require long monitoring sessions. EEG systems that operate for several hours often need to optimize their energy consumption, which may involve reducing the sampling rate or channel density, once again impacting data quality and real-time synchronization.

Table 2-1: Dispositivos de adquisición utilizados para BCI. La tabla ofrece una descripción general de los diferentes dispositivos de hardware, sus especificaciones y protocolos de comunicación.

Hardware BCI	**Empresa**	**Tipo de Electrodo**	**Canales**	**Frecuencia de Muestreo**	**AFE**	**Protocolo y Transferencia de Datos**	**Duración de la Batería**
Cyton + Daisy [?]	OpenBCI	Flexible / Húmedo / Seco	16	250 Hz- - 16 kHz	ADS1299	RF / BLE / Wi-Fi	8 h
actiCAP [?]	Brain Products GmbH	Flexible / Húmedo / Seco	16	256 Hz- - 16 kHz	-	USB	16 h
EPOC X [?]	Emotiv	Rígido / Húmedo	14	128 Hz	-	BLE / Bluetooth	6–12 h
Diadem [?]	Bitbrain	Rígido / Seco	12	256 Hz	-	Bluetooth	8 h
g.Nautilus [?]	g.tec	Flexible	8 / 16 / 32	250 Hz	ADS1299	Propietario	10 h
Plataforma para EEG ambulatorio [?]	-	Activo / Seco	32	250 Hz- - 1 kHz	ADS1299	Wi-Fi 802.11 b/g/n	26 h
Sistema para neurofeedback [?]	-	Pasivo / Seco	40	250 Hz	ADS1298	RF	-
BEATS [?]	-	Flexible / Húmedo	32	4 kHz	ADS1299	Wi-Fi	24 h (cableado)

In the field of brain-computer interfaces (BCIs), several devices have been developed, each with unique features tailored to specific use cases such as clinical research, neurofeedback, or consumer applications. The Cyton + Daisy system by OpenBCI [?] supports up to 16 channels and offers a wide sampling rate range of 250 Hz to 16 kHz, making it suitable for high-resolution EEG acquisition. The device uses flexible, wet, or dry electrodes and incorporates the ADS1299 AFE for high-quality signal conversion. It supports data transfer via RF, Bluetooth Low Energy (BLE), and Wi-Fi, allowing for versatile connectivity. With a battery life of 8 hours, this system is highly adaptable, suitable for both research and practical applications in various environments. Another system, actiCAP [?] by Brain Products GmbH, features flexible, wet, or dry electrodes and is capable of recording up to 16 channels with a sampling rate range from 256 Hz to 16 kHz. The actiCAP does not use a dedicated AFE and instead relies on a USB protocol for data transfer. The device provides a robust 16-hour battery life, making it an ideal choice for long-duration experiments and clinical settings that require stable signal acquisition over extended periods. The EPOC X [?] by Emotiv is a more compact and consumer-oriented BCI device that uses rigid, wet electrodes and supports 14 channels with a sampling rate of 128 Hz. This device employs Bluetooth Low Energy (BLE) for wireless data transfer, and its battery life ranges from 6 to 12 hours, depending on usage. While its lower sampling rate may limit its use for high-resolution research, the EPOC X remains a popular choice for applications in neurofeedback, cognitive training, and general user interaction. The Diadem [?] system by Bitbrain uses rigid, dry electrodes and supports 12 channels with a sampling rate of 256 Hz. It operates via Bluetooth for data transmission and has a battery life of 8 hours, providing a balance between portability and signal quality. The g.Nautilus [?] system by g.tec offers great flexibility, supporting configurations with 8, 16, or 32 channels. It operates at a sampling rate of 250 Hz and uses the ADS1299 AFE for high-performance signal acquisition. The system is known for its proprietary data transmission protocol, ensuring reliable connectivity, and its battery lasts up to 10 hours, making it suitable for long-term monitoring and research studies. The BCI system used by [?] employs active, dry electrodes and supports up to 32 channels with a sampling rate range of 250 Hz to 1 kHz. It also incorporates the ADS1299 AFE for analog-to-digital conversion, ensuring high fidelity in signal capture. Data is transferred via Wi-Fi 802.11 b/g/n, enabling flexible and high-speed communication with external devices. The system boasts an impressive 26-hour battery life, making it an excellent option for extended usage in field studies or clinical applications. The BCI system described by [?] uses passive, dry electrodes and supports up to 40 channels with a sampling rate of 250 Hz. It incorporates the ADS1298 AFE for high-quality data acquisition and utilizes RF (Radio Frequency) for data transfer. While battery life details are not specified, this device is likely designed for portable, research-focused applications where wireless data transfer is essential for real-time monitoring. Finally, the [?] system features 32 flexible, wet electrodes and uses the ADS1299 AFE for high-precision EEG signal acquisition at a sampling rate of 4 kHz. Data is transmitted wirelessly via Wi-Fi, allowing for real-time data monitoring and analysis. The system's battery life is 24 hours when wired, providing extended operation for intensive studies or clinical assessments that require continuous monitoring.

Each of these devices represents a different approach to EEG signal acquisition, offering varying numbers of channels, electrode types, sampling rates, and battery life. While some are optimized for research and clinical use with high sampling rates and extended battery life, others are more suited to consumer applications with lower sampling rates and shorter operational times. The choice of device depends largely on the specific needs of the user, whether for research, clinical monitoring, or personal use in neurofeedback and cognitive training applications.

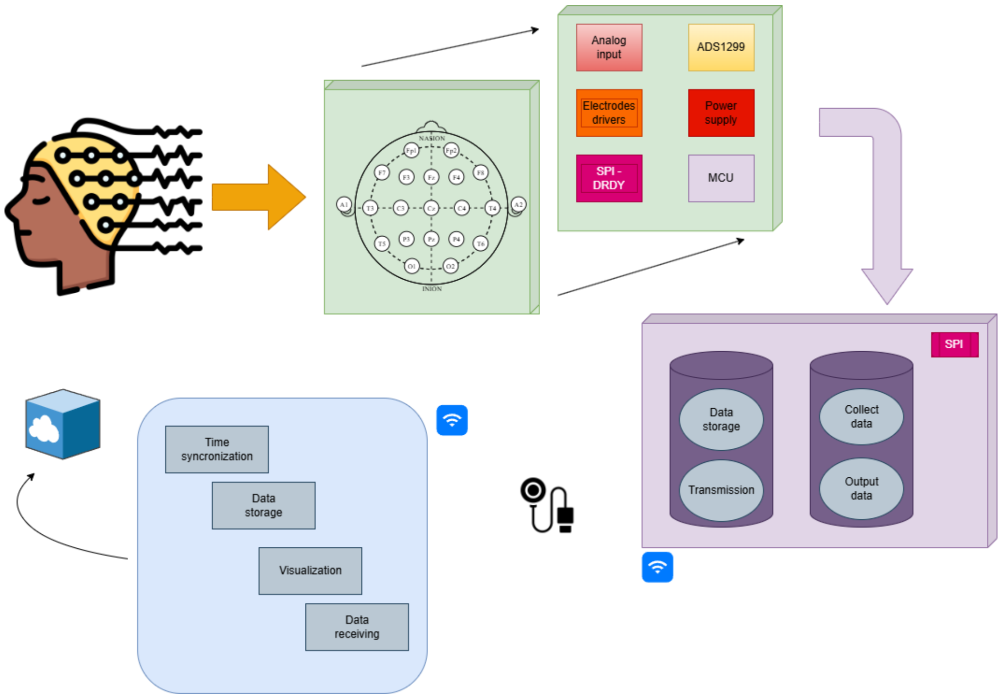

Figure 2-1: Arquitectura de MONEEE

2.2 Arquitectura

- Descripción General

  MONEEE es un sistema avanzado diseñado para la adquisición y procesamiento de señales electroencefalográficas (EEG), con un diseño modular y escalable. Este sistema consta de varios módulos interconectados que aseguran una alta precisión en la captura de datos, estabilidad durante el proceso de adquisición y flexibilidad para su aplicación en investigación y diagnóstico clínico. Los electrodos, posicionados según el sistema 10-20, capturan señales eléctricas del cerebro y las transmiten a un módulo de conversión analógica a digital. Posteriormente, estas señales digitalizadas son gestionadas por un microcontrolador, que no solo regula el flujo de datos, sino que también monitorea la calidad de las señales adquiridas. Finalmente, el sistema se conecta a una plataforma de software que permite la visualización en tiempo real, el almacenamiento seguro de datos en servicios en la nube y la sincronización precisa con los eventos experimentales, facilitando así el análisis posterior, como se muestra en la figura **2-1**.

- Módulo de Transmisión

  El módulo de transmisión de MONEEE sirve como el centro neurálgico que conecta la adquisición de señales con su procesamiento y visualización externa. Consiste en varios subsistemas clave que operan de manera cohesionada:

- Módulo de Conversión Analógico-Digital

En el núcleo del módulo de adquisición se encuentra el ADS1299 de Texas Instruments [?], un convertidor analógico-digital (ADC) de alta precisión diseñado específicamente para aplicaciones de monitoreo biológico como EEG, EMG y ECG. Este ADC presenta características que lo hacen ideal para capturar señales de baja amplitud, típicas de la actividad cerebral, como una resolución de 24 bits y un alto rango dinámico capaz de detectar variaciones sutiles en la actividad cerebral.

El ADS1299 incluye múltiples canales de entrada que pueden operar simultáneamente, lo que permite una adquisición de datos sincronizada. Además, tiene filtros digitales incorporados, como filtros pasa-bajo y notch, que ayudan a reducir el ruido y mejorar la relación señal-ruido antes de que las señales sean digitalizadas. Su capacidad para trabajar en configuraciones en cascada permite conectar hasta ocho módulos ADS1299, lo que soporta configuraciones de adquisición de datos de hasta 64 canales. Esto es esencial para estudios avanzados que requieren una cobertura amplia y detallada de la actividad cerebral.

- Transmisor

  El sistema de transmisión de MONEEE está diseñado para garantizar una transferencia rápida y confiable de los datos digitalizados a un dispositivo externo, como una computadora o servidor. Emplea un sistema de comunicación serial de alta velocidad, utilizando protocolos como UART o SPI, optimizados para minimizar la latencia durante la transmisión. Este enfoque asegura que los datos adquiridos puedan ser procesados o visualizados en tiempo real sin retrasos o pérdidas significativas, lo cual es crítico para aplicaciones que requieren una sincronización precisa, como experimentos en neurociencia o estudios clínicos con estimulación sincronizada.

  Para asegurar conexiones eficientes y adaptables, el sistema puede integrar conversores USB-a-serial, lo que permite la compatibilidad con computadoras modernas sin interfaces seriales nativas. Además, MONEEE puede incorporar transmisores inalámbricos, como módulos Bluetooth o Wi-Fi, para situaciones donde la movilidad o la eliminación de cables sea crucial. Sin embargo, la arquitectura inicial se centra en interfaces seriales por cable para priorizar la baja latencia y estabilidad.

- Microcontrolador

  El microcontrolador elegido para MONEEE debe manejar un alto volumen de datos provenientes de hasta 64 canales de EEG simultáneamente, además de supervisar los procesos de adquisición y comunicación. Una opción adecuada es el STM32H7 de STMicroelectronics [?], basado en un núcleo ARM Cortex-M7. Este microcontrolador combina un rendimiento excepcional con una memoria RAM amplia y capacidades de procesamiento en tiempo real.

  El STM32H7 incluye múltiples interfaces de comunicación, como SPI, I2C y UART, lo que permite la integración directa con los módulos ADS1299 y de transmisión. Su capacidad para manejar tareas paralelas asegura que pueda controlar múltiples módulos ADS1299 en configuraciones en cascada, gestionar la transmisión de datos a dispositivos externos y realizar operaciones de preprocesamiento básico, como detección de artefactos o validación de datos.

Además, su soporte para módulos de comunicación inalámbrica, incluyendo BLE y Wi-Fi, lo hace adaptable para futuras expansiones del sistema. Esto asegura que MONEEE no solo cumpla con los requisitos actuales de adquisición, sino que también sea escalable para necesidades futuras.

- Software

  La plataforma de software de MONEEE está diseñada como una herramienta integral que proporciona visualización, almacenamiento y análisis de los datos de EEG. Esta plataforma, desarrollada con una interfaz gráfica amigable, permite a los investigadores y usuarios clínicos monitorear señales EEG en tiempo real con representaciones gráficas interactivas, incluyendo visualizaciones del espectro de frecuencias, tendencias temporales y patrones espaciales.

  El software también se conecta a servicios de almacenamiento en la nube, lo que permite la copia de seguridad automática de los datos adquiridos y su accesibilidad para análisis remotos. Esta funcionalidad es esencial para proyectos colaborativos o investigadores que necesitan acceso a los datos desde diferentes ubicaciones geográficas.

  Además de las características de visualización, la plataforma incluye un sistema de sincronización temporal que permite registrar eventos experimentales y asociarlos con las señales EEG correspondientes. Esto es particularmente útil en estudios que combinan estimulación visual o auditiva, ya que facilita la identificación de respuestas cerebrales específicas ante estímulos dados.

  Las futuras implementaciones del software planean incluir herramientas de análisis automatizado basadas en inteligencia artificial, lo que permitirá a los investigadores identificar patrones complejos en los datos de EEG y generar informes detallados automáticamente.

3 System Architecture and Design Requirements

3.1 High-Level System Architecture

4 Analog Front End implementation

4.1 Sensor