Developing an AI-Driven Framework for Real-Time Signal Processing and Data Exchange

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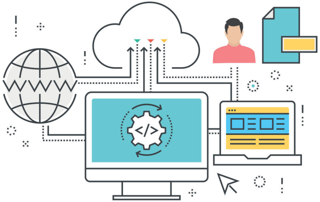
Outline

Data Exchange refers to the **efficient and secure** flow of data between different platforms and procedures [Zhang et al., 2021, Thakare and Kim, 2021].



It requires strong security and encryption, data quality and dependability, and industry-specific **compliance standards** [Attiogbé et al., 2021].

- Business intelligence and analytics [Kouper and Cook, 2021].
- Finance and banking [Elsaify and Hasan, 2021].
- Government and public services [Ball et al., 2020].
- Marketing and advertising [Mishra and Kaushik, 2023].
- Healthcare [Al-Kahtani et al., 2022].
- Research and academia [Qiu et al., 2021, Paltun et al., 2021, Adiga et al., 2022].

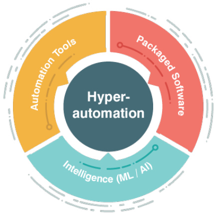
Motivation
The Growth of Data Centers in Colombia

Latin America's technological revolution plays a crucial role in promoting **regional economic growth**, closing the digital gap, creating a foundation for improved connectivity, innovation, and robust digital infrastructure [Global Services Location Index, 2021].

- Fourth largest data center market in Latin America.
- Significant investments in infrastructure.
- Attractive for international investments.
- Strategic location advantage.

Hyperautomation elevates traditional software automation, infusing it with AI to transform data ecosystems into adaptive, **self-optimizing entities**, reshaping the dynamics of data management and analysis.

- Data Process Automation
- Analysis and Decision-Making
- Workflow Optimization
- System Integration
- Data Governance
- Scalability and Maintenance



Integrating **AI** into software transforms data ecosystems into intelligent, self-evolving networks, revolutionizing the approach to data management and analysis. [Haleem et al., 2021].

Motivation

SPRG: Signal Processing and Recognition Group

Our research group develops **transdisciplinary data exchange** since we know that it exposes novel approaches and supports collaborative discoveries **across academic areas** [Gomez Rivera, 2023, Aguirre-Arango et al., 2023].

- Data heterogeneity.
- Handling unstructured data.
- Real-Time Data Processing and Exchange.
- Privacy and security regulations.
- Interoperability and accessibility.
- Scalability and efficient management.

APIs: They are limited by request rate, security, and provider stability/changes [Velepucha and Flores, 2023].

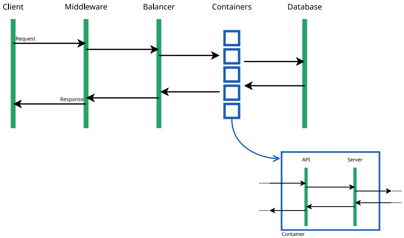
ETL: Performance and complexity concerns related to data quality and handling large amounts of diverse data. [Abdelhafiz and Elhadef, 2021].

Messaging: Scalability, delivery assurance, state management, and security issues in distributed systems. [Fang et al., 2019].

File Transfer: Security, file size, and bandwidth issues [Ordóñez et al., 2023, Yi et al., 2023].

Problem Statement
API Request Limits

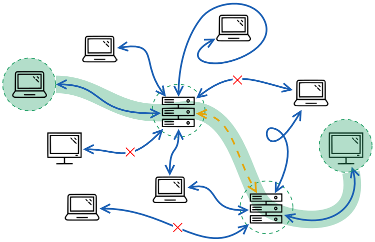
API request **rate limits** may cause data transmission difficulties, especially in multimodal and real-time situations, and make API provider changes **harder to adapt** and maintain [Malki et al., 2022, Malki and Zdun, 2023].



Manual configurations limit API effectiveness in multimodal and real-time environments.

Scalability and delivery certainty problems in distributed messaging systems can lead to the **loss or delay of messages**, which can have a severe influence on the **efficiency and reliability** of communication in real-time and multimodal contexts

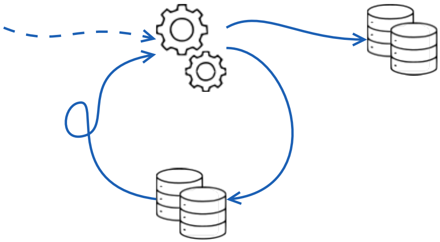
[Arellanes and Lau, 2020, Basin et al., 2020].



Centralized server reliance in distributed messaging often results in inefficient routing.

Complex multimodal ETL processes can lead to **inaccurate data and disruptions** in AI analysis due to challenges with data integration and real-time data management

[Qaiser et al., 2023, Soussi, 2021].

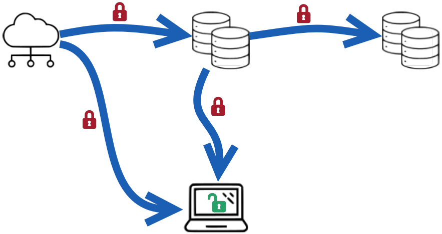


Relying on rigid, sequential data handling poses challenges in data integration and real-time management .

Problem Statement

Large-Scale File Transmission

Large-scale file transmission requires efficient and safe administration of continuous data flow, especially in integrating systems and platforms, while ensuring data **integrity** and **accessibility** in changing contexts [Zheng et al., 2020, Yin et al., 2023].



Depends primarily on protocols that are static and universally applicable.

State-of-the-Art

APIs: Infrastructure Improving

- Optimization in Computer Systems
  - Real-Time Systems
    - Towards Self-Managing Cloud Storage with Reinforcement Learning [Noel et al., 2019].
    - On the Design and Implementation of Real-Time Resource Access Protocols [Dos Santos et al., 2020].
  - Communication Efficiency
    - Adaptive REST API Testing with Reinforcement Learning [Kim et al., 2023].
    - Event-Triggered Communication Network with Limited-Bandwidth Constraint for Multi-Agent Reinforcement Learning [Hu et al., 2021].
  - Resource Management
    - Online Task Allocation and Scheduling in Fog IoT using Virtual Bidding [Joshi and Srivastava, 2022].
    - Dynamic Resources Management Under Limited Communication Based on Multi-level Agent System [Wang et al., 2023].

*Limitations in **real-time API performance** and **adaptability** due to static configuration settings.*

State-of-the-Art

Distributed Messaging: Scalability and Reliability

- Distributed Real-Time Messaging and Scalability
  - IoT and Scalable Architectures
    - PISTIS: An Event-Triggered Real-Time Byzantine-Resilient Protocol Suite [Kozhaya et al., 2021].
    - Towards Scalable Cross-Chain Messaging [Otavio Chervinski et al., 2023].
    - Designing a Real-Time IoT Data Streaming Testbed for Horizontally Scalable Analytical Platforms [Štufi and Bačić, 2021].
  - Event Streaming and Async. Communication
    - Adaptive Topology for Scalability and Immediacy in Distributed Publish-Subscribe Messaging [Banno and Shudo, 2020].
    - Reliability enhancements for high-availability systems using distributed event streaming platforms [Dincă et al., 2023].

Inefficiencies and scalability issues *in distributed messaging systems affecting real-time communication.*

State-of-the-Art

AI-Enhanced ETL Processes

- Data Integration and Real-Time Management
  - Advances in Disease Detection and Analysis
    - Deep Learning Applications in Vessel Dead Reckoning to Deal with Missing Automatic Identification System Data [Sedaghat et al., 2024].
    - Deep learning from latent spatiotemporal information of the heart [Chang et al., 2024].
    - Machine Learning Revolution in Early Disease Detection for Healthcare [Reddy et al., 2023].
  - Real-Time Health Monitoring
    - Data pipeline for real-time energy consumption data management and prediction [Im et al., 2024].
    - Integrating IoT and Machine Learning for Real-Time Patient Health Monitoring with Sensor Networks [Vimal et al., 2023].

*Inefficiencies in processing **unstructured and temporal data** in AI-driven multimodal ETL systems.*

State-of-the-Art

Advancements in Large-Scale File Transmission

- Data Flow Management and Large-Scale File Transmission
  - Coding Techniques and Distributed Systems
    - Survey of Network Coding Based P2P File Sharing in Large Scale Networks [AbuDaqa et al., 2020].
    - Network coding for efficient file transfer in narrowband environments [Yin et al., 2023].
    - Design and Optimization of a Distributed File System Based on RDMA [He et al., 2023].
  - Protocols and Network Security
    - The Design of Intelligent Transportation Video Processing System in Big Data Environment [Hao and Qin, 2020].
    - Reliable, Efficient Large-File Delivery over Lossy, Unidirectional Links [Van Besien et al., 2021].

*Challenges in ensuring **efficient and secure** large-scale file transmission in **varying network conditions**.*

Question Research

How can advanced artificial intelligence and machine learning techniques enhance data management and communications in digital environments? Specifically, in improving real-time API flexibility and effectiveness, boosting distributed messaging system efficiency and scalability, effectively processing unstructured and temporal data in multimodal ETL systems, and optimizing large-scale file transmission under varying network conditions?

General Objectives

To develop an **AI-driven framework** that enhances **real-time management** of signal and data processing across network protocols, with a focus on efficiency, security, scalability, and responsiveness, ultimately **improving research capabilities** and facilitating seamless data exchange.

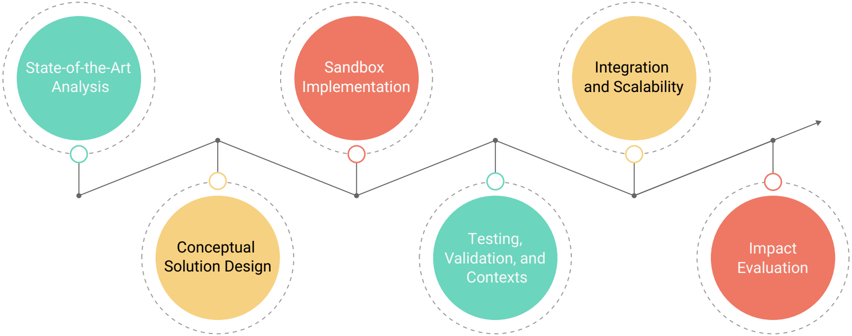
Specific Objectives

1. To design a **multichannel time series processing strategy** to enhance and strengthen the structure for immediate collection and display of various types of signals, with a specific emphasis on **streamlining and parameterizing** the required infrastructure for experiments and **merging different types of signals** into a single interface.

2. To implement an **AI strategy** to improve the control of **real-time APIs** and **multimodal ETL processes** through the utilization of **advanced machine learning and deep learning methods** to enhance precision, effectiveness, and promptness in intricate data processing and analysis.

3. To create an **AI-based advanced platform** for transmitting **large files** and **distributing messages** on a large scale. This system will utilize artificial intelligence technologies to improve efficiency, security, and scalability, and will also be capable of **adjusting to changing network conditions** to boost communication and data transfer.

General Methodology of Contributions



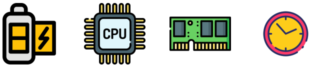
A six-step approach to analyze, design, prototype, test, integrate, and evaluate real-time AI-driven solutions.

AI Hyperparameter Tuning and System-Level Optimization

Enhancing Model Performance and System Efficiency through Dual Optimization Techniques

Joint Optimization Approach

- Optimize both **model hyperparameters** and **system resources** (CPU, memory, latency, energy) to enhance overall performance.



Reinforcement Learning (RL) for Adaptive Optimization

- **RL** adjusts **system resources** (CPU/GPU, memory, network) in real-time to maintain efficiency under changing conditions.

Synergy Between Techniques

- **Bayesian Optimization** finds optimal initial configurations.
- **RL** continuously adapts configurations to maintain **efficiency** under different operational conditions.

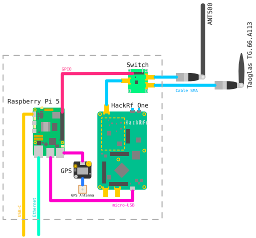
*By integrating **Bayesian optimization** for initial setup with **reinforcement learning** for continuous adaptation, the goal is to achieve **robust performance** and **resource efficiency** under diverse system conditions.*

Testing Contexts of Interest

Scenarios for Testing

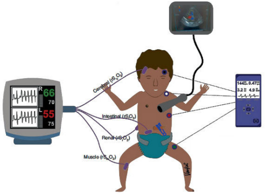
Prototipo costo-eficiente y escalable para el monitoreo del espectro radioeléctrico en Colombia mediante radio definido por software y aprendizaje profundo.

- Scalability
- Robustness
- Low Latency
- Reliability



Sistema de integración de EEG, ECG y SpO2 para seguimiento de neonatos en unidad de cuidados intensivos del Hospital Universitario de Caldas - SES HUC.

- Real-Time Monitoring
- Data Centralization
- Alarm Generation
- Accuracy in Critical Settings



Two diverse research projects provide essential testing environments for validating scalability, robustness, and real-time data integration as part of the system development methodology.

Testing Contexts of Interest

Scenarios for Testing

Prototipo Funcional de Lengua Electrónica para la Identificación de Sabores en Cacao Fino de Origen Colombiano.

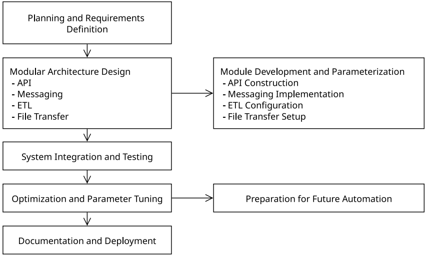
- Flavor Profile Identification
- Portability and Real-Time Analysis
- Quality Validation

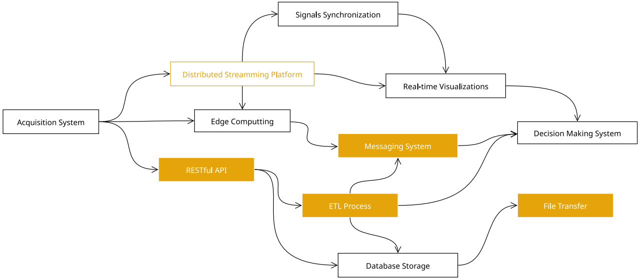
Together, these three projects provide a **comprehensive validation of the AI-driven solution, enhancing robustness, adaptability**, and practical applications across sectors from telecommunications to food quality.

The electronic tongue prototype supports research by providing a practical testing environment for enhancing flavor analysis methodologies in cacao production.

Methodology [OBJ1]

Streamlining Signal Integration:
A Comprehensive Approach to Real-Time Data Management and Visualization

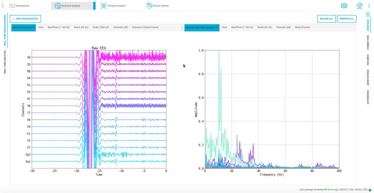


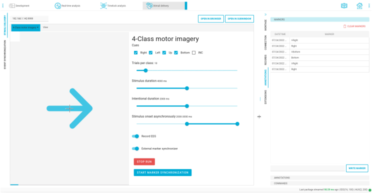


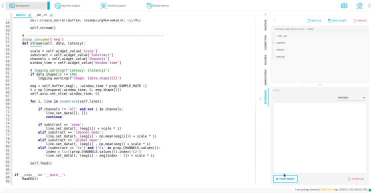
*Create a **modular and parameterized** system for real-time signal acquisition, processing, and integration.*

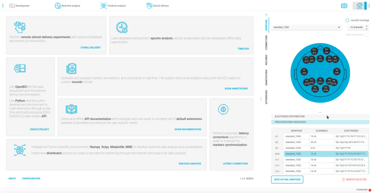
Methodology [OBJ1]

BCI-Framework V1.0







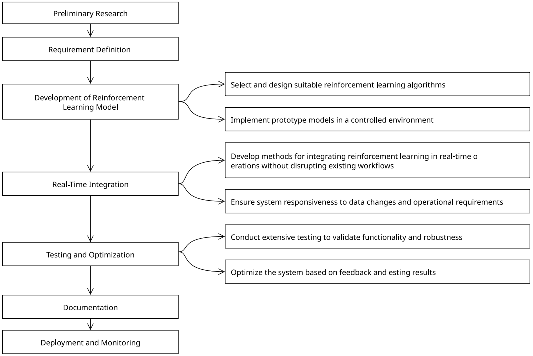


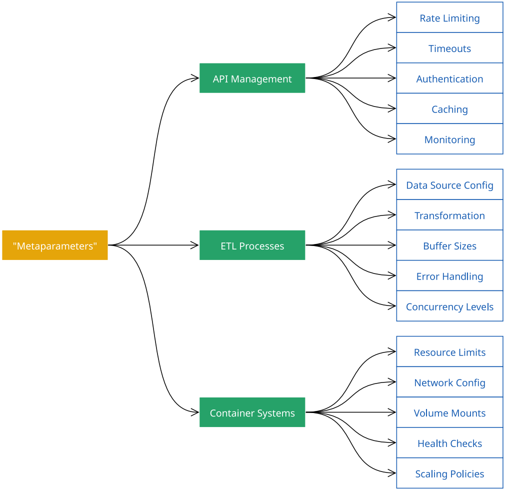
GitHub: https://github.com/UN-GCPDS/bci-framework

Documentation: https://bci-framework.readthedocs.io/en/latest/

Methodology [OBJ2]

Optimizing System Performance: Configuring Key Parameters for Enhanced Efficiency and Security





*Implement **AI-driven automation** for optimizing real-time API and ETL configurations.*

Methodology [OBJ2]

Scalable Service Management for AI Applications

Foundation is a scalable AI framework for managing distributed services and data processes, designed to optimize efficiency and flexibility in Docker Swarm environments.

- **Service Management:** Automates creation, deletion, and scaling of services in Docker Swarm.
- **Worker Lifecycle Control:** Manages Python, Django, and Brython services, ensuring efficient deployment and operation.
- **Distributed Logging:** Centralized log management via HTTP and Kafka for better monitoring.
- **Dynamic Resource Allocation:** Adaptive management of CPU, memory, and network resources to optimize performance.
- **Integration with AI Models:** Supports integration of machine learning models for automated decision-making and optimization.

GitHub: https://github.com/dunderlab/python-dunerlab.foundation

Documentation: https://dunderlab-foundation.readthedocs.io/en/latest/index.html (Not yet)

Methodology [OBJ3]

Building Advanced AI-based Network protocols: Enhancing Communication and Data Transfer Efficiency

Preliminary Study and Technology Review

System Architecture Definition
- Integration of Messaging and Remote code interpretation
- Serverless and graph-distributed design

Integration of AI Technologies
- Optimization of routing and security
- Adaptation to network changes

Prototype Developmen and Initial Testing

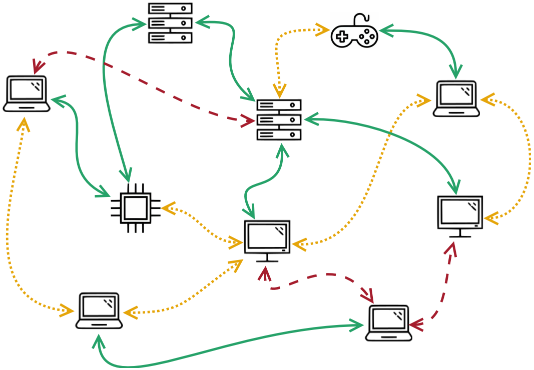
Distribution Optimization and Scalability

Task Automation and Parameterization

Complete Implementation and Stress Testing

Documentation

Launch and Continuous Monitoring



*Build a scalable, **AI-enhanced platform** for efficient file transmission and distributed messaging.*

Methodology [OBJ3]

Dynamic Communication Framework for Distributed Networks

Chaski-Confluent is a distributed communication framework designed for scalable message handling and dynamic node pairing, tailored for TCP/IP networks and optimized for efficient data exchange.

- **Scalable Messaging:** Supports robust node discovery and efficient message routing in large-scale networks.
- **Dynamic Node Pairing:** Manages automatic pairing of nodes based on subscription topics, ensuring adaptive communication.
- **Remote Python Execution:** Facilitates remote Python script execution similar to RPyC, enhancing computational flexibility.
- **AI-Enhanced Data Transfer:** Integrates AI-based techniques for optimizing large file transfers and message distribution.
- **Real-Time Adaptability:** Adjusts to network changes for improved communication and resource utilization.

GitHub: https://github.com/dunderlab/python-chaski
Documentation: https://chaski-confluent.readthedocs.io/en/latest/

Obtained Results
Papers

[2023] Published a research paper titled **"A Novel OpenBCI Framework for EEG-Based Neurophysiological Experiments"** in the journal Sensors. The paper discusses the development of an Open Brain-Computer Interface (OpenBCI) framework, utilizing open-source hardware and firmware to facilitate EEG-based neurophysiological experiments. The framework is designed to overcome the limitations of OpenBCI systems, particularly in communication and flexibility for various neurophysiological protocols. The research was published in Volume 23, Issue 7 of Sensors, 2023 (DOI: 10.3390/s23073763) (MDPI).

[2023] At the "III Congreso Latinoamericano de Investigación, Innovación y Emprendimiento Educativo," presented **"Real-Time Processing for BCI-Based MI Paradigms Using Deep Learning Models"** This paper showcases advancements in BCI technology, highlighting the application of deep learning models for efficient, real-time processing in Motor Imagery (MI) paradigms. The study emphasizes improvements in processing speed and accuracy, addressing challenges in real-time applications and setting new standards for BCI system performance. The work has significant implications for both academic research and practical BCI applications in various fields.

Obtained Results

Patents and software registers

[2022] The systems were submitted to the Crearlo no es suficiente summons for a patentability search process with the Universidad Nacional de Colombia sede Manizales as main beneficiary with the title **"MÉTODO Y SISTEMA PARA LA SINCRONIZACIÓN DE MARCADORES ASOCIADOS A SISTEMAS DE INTERFAZ CEREBRO-COMPUTADOR"**, postulation ID 343 and Application number NC2022/0007405 from May 28, 2022.

[2022] A script developed with BCI-Framework for **Motor imagery paradigm with game-based stimulus (Pacman interface)** was submitted to the software register in the Universidad Nacional de Colombia sede Manizales.

Implementation Schedule

Months	Activities						
	Phases OBJ 1	Phases OBJ 2	Phases OBJ 3	Papers and thesis document writing			
				Paper	Paper	Paper	Thesis
1-2							
2-4							
4-6							
6-8							
8-10							
10-12							
12-14							
14-16							
16-18							

Acknowledgements

This research would not have been possible without the support provided by the project *Prototipo Funcional de Lengua Electrónica para la Identificación de Sabores en Cacao Fino de Origen Colombiano (código 202010039703)* funded by **Casa Luker**.

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