ScuDo
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38th Cycle

Brain-to-Brain Communication Based on Semantic Features in EEG Signals

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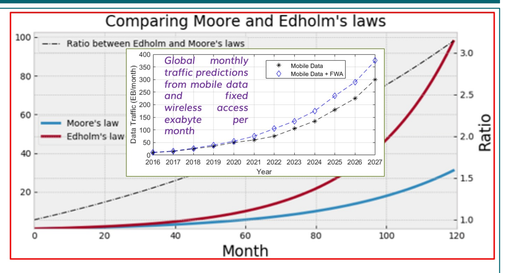
Research context and motivation

❖ In the era of information explosion, classical bit-based communication systems are hitting their limits, as evidenced by Edholm's and Moore's laws, which signal an impending bottleneck in our ability to manage and transmit information. This calls for an urgent paradigm shift in how we approach communication technologies.



❖ Semantic communication emerges as a compelling alternative, which, unlike traditional methods, focuses on the meaning and context of the information being transmitted, offering a more efficient and nuanced form of data exchange.

❖ As the primary source of semantic information, the brain presents an untapped frontier for revolutionizing this field. It holds the key to moving beyond mere data transmission to a more evolved form of communication that includes understanding, interpretation, and decision-making.

❖ Electroencephalogram (EEG) signals provide a secure and reliable avenue for advanced Brain-to-Brain Communication (B2BC), as demonstrated in preliminary animal studies. To further this field, it's crucial to address existing challenges by optimising semantic features in EEG signals for more secure and efficient B2BC. This involves enhancing brain synchronisation, focusing on parameters like Root Mean Square (RMS) of EEG potentials, and considering adaptive bit rate control in semantic communication.

❖ The transition from data-driven to knowledge-driven networks is not just imminent but imperative. This thesis aims to leverage mathematical modelling and algorithms to explore how semantic features in EEG signals can be optimized for effective and secure Brain-to-Brain Communication.

Addressed research questions/problems

❖ **How can semantic features in EEG signals be reliably captured and extracted?**
Identifying reliable EEG devices and relevant channels; developing algorithms for feature extraction.

❖ **What are the key parameters for effective and secure B2BC?**
Considering RMS in EEG potentials, focusing on latency, bandwidth, and data security.

❖ **How does semantic-based B2BC improve upon traditional methods?**
Comparing efficiency and reliability; developing metrics for performance measurement, including "Reasoning Capacity".

Novel contributions

❖ **Stacking Decision-MultiLayer Perceptron (SD-MLP)**: Introducing a novel ensemble model that combines multiple machine learning classifiers to improve EEG-based Motor Imagery classification.
❖ **Machine Learning Classifiers**: Employing 16 different machine learning classifiers for comparative analysis.
❖ **Adversarial Neural Network Training (ANNT):** Applying ANNT to enhance the robustness and security of EEG-based Brain-to-Brain Communication systems.

Attended Courses

1. Adversarial training of neural networks CFU (3)
2. Communication CFU (1)
3. Design Thinking, Processes and Methods CFU (0.4)
4. Lingua italiana I livello CFU (3)
5. Managing conflict: negotiation and communication CFU (1)
6. Public speaking CFU (1)
7. Personal branding CFU (1)
8. Strutture dati in Python CFU (4)
9. Project management CFU (1)
10. Thinking out of the box CFU (1)
11. Time management CFU (1)
12. Programmazione scientifica avanzata in matlab CFU (6)
13. Optimized execution of neural networks at the edge CFU (5)
14. Instrumentation and Measurement for Brain-Computer Interfaces (didattica di eccellenza) CFU (2)

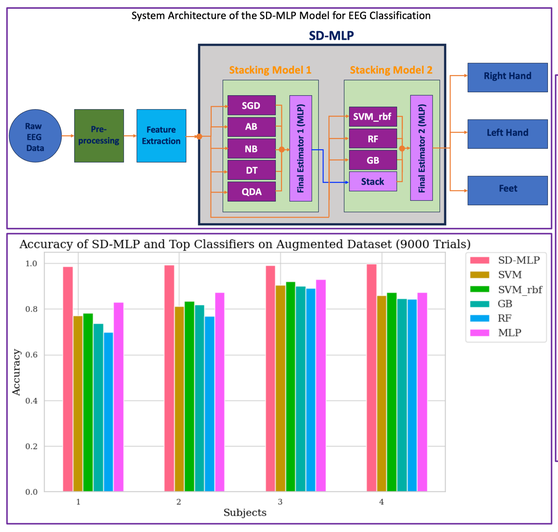
Publications

- Submitted work: H. Ahmadi and L. Mesin, "A Novel Stacked Ensemble Approach for EEG-Based Motor Imagery Classification," submitted to IEEE Trans. Neural Syst. Rehabil. Eng.
- To be Submitted: H. Ahmadi and L. Mesin, "Adversarial Neural Network Training for Secure and Robust Brain-to-Brain Communication," to be submitted to IEEE Trans. Neural Netw. Learn. Syst.

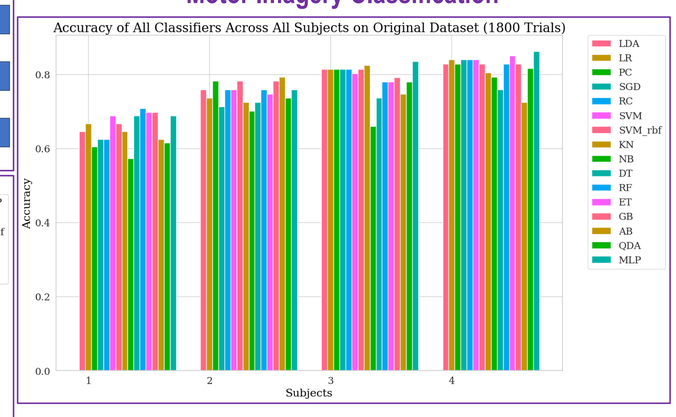
Adopted methodologies

❖ **Data Preprocessing**: Using a 7-30 Hz band-pass filter and SMOTE for class balancing.
❖ **Feature Extraction**: Utilizing Common Spatial Patterns (CSP) and Convolutional Neural Networks (CNN) for spatial feature extraction.
❖ **Model Training**: Employing 10-fold cross-validation, hyperparameter tuning via grid search, and data augmentation through boosting techniques.
❖ **Advanced Modeling**: Utilizing Temporal Convolutional Network (TCN) for capturing temporal dependencies.
❖ **Real-world Simulation**: Simulating a noisy and perturbed wireless channel for real-world applicability.

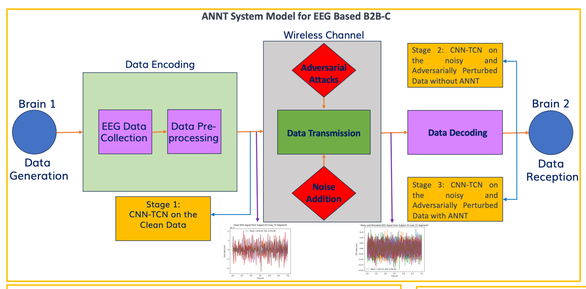
Results

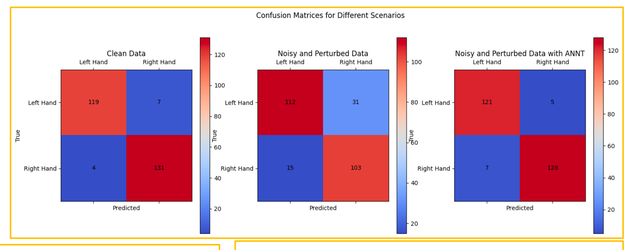


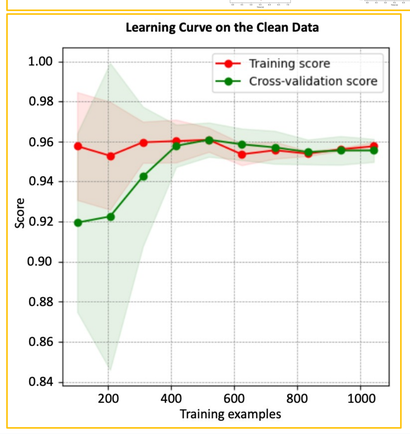
A Novel Stacked Ensemble Approach for EEG-Based Motor Imagery Classification

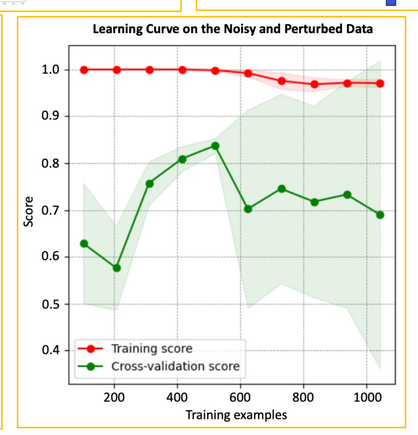


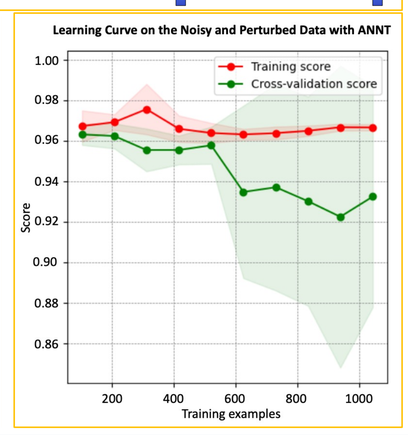
Adversarial Neural Network Training for Secure and Robust Brain-to-Brain Communication











Future Research Directions

1. **Methodological Advancements**:
   - Adapt current methodologies for feature extraction and machine learning algorithms for optimization to suit the needs of future semantic-based B2BC technologies.
2. **Semantic Resonance Decoder (SRD)**:
   - **Concept**: A novel algorithm for real-time semantic feature extraction from EEG signals.
   - **Functionality**: Map EEG patterns to a semantic library for each individual.
   - **Application**: Enhanced emotional communication, beneficial for those with communication disorders.
3. **Optimized B2BC Parameters**:
   - Focus on latency, bandwidth, and RMS in EEG potentials.
   - Implement advanced security metrics like Semantic Confidence and encryption mechanisms.
4. **Comparative Analysis & Metrics**:
   - Develop a framework for comparing semantic-based B2BC against traditional methods.
   - Introduce the ground-breaking "Reasoning Capacity" metric.
5. **Semantic Resonance Interface (SRI)**:
   - **Semantic Mapping Layer**: Build upon the existing comparative analysis framework to develop a deep learning model that translates brain activity into a universal semantic language.
   - **Dynamic Resonance Chamber**: Utilize the "Reasoning Capacity" metric to create a virtual environment for real-time interaction of semantic features.
   - **Multi-Modal Integration**: Explore the possibility of integrating additional biometric data, like eye movement and facial expressions, to enrich the semantic features.
6. **Technologies Beyond 5G & Reasoning Capacity**:
   - Explore the potential of emerging technologies to enhance the performance and security of future semantic-based B2BC technologies.
   - Further refine and validate the "Reasoning Capacity" metric in the context of these advanced systems.

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PhD program in
Electrical, Electronics and Communications Engineering