POST-DIGITAL - European Training Network on Post-Digital Computing [GA860360]

Document Details

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Project Details

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Start of the Project	1 April 2020
Project Duration	48 months

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860360.

Executive Summary

POST-DIGITAL recruited and employed on full-time contracts 15 Early Stage Researchers (ESRs). All ESRs were registered for a PhD at their host organisation, or where this was an industrial organisation, at an affiliated academic university from within the consortium. The majority of ESRs (9 in total) are on 4-year PhD tracks (with the 4th year funded from other sources within the organization) and are therefore not yet able to submit their PhD research for examination but will do so in the next 6-8 months. Six ESRs are on a 3-year PhD track and about to submit their theses. One PhD student (ESR6 at Thales) has submitted his thesis, currently awaiting its defence. One ESR (ESR 10) resigned for personal reasons.

This deliverable gives full details of the current state of all PhD students' theses, including open access links and abstracts where available.

TABLE OF CONTENTS

LIST OF ACRONYMS

EC	European Commission
ESR	Early Stage Researcher
ETN	European Training Network
POST-DIGITAL	Project 'POST-DIGITAL - European Training Network on Post-Digital Computing' EC GA 860360

ESR 1: Mr Steven Abreu

Name	Steven Abreu
Host beneficiary:	University of Groningen
Employment start date	1 Jan 2021
PhD Enrolment (University name)	University of Groningen
PhD length	4 years, extended to 5+ years through industrial internships
Main Supervisor:	Herbert Jaeger (Groningen)
Industrial Supervisor	Peter Bienstman (IMEC)
PhD thesis title:	Information coding in nonlinear dynamical substrates
PhD thesis submitted	Not yet submitted as on >4 year PhD track; expected Dec 2025
PhD defence date:	Not yet available as on >4-year PhD track
Access to Full Text (Open Access)	Not available yet as on >4-year PhD track
PhD Thesis Abstract	
Not yet available as on >4-year PhD	

ESR 2: Mr Guillaume Pourcel

Name	Pourcel Guillaume
Host beneficiary:	University of Groningen
Employment start date	1 November 2020
PhD Enrolment (University name)	University of Groningen
PhD length	4 years
Main Supervisor:	Herbert Jaeger (Groningen)
Industrial Supervisor	Tobias Delbruck (iniLabs)
PhD thesis title:	Robust cognitive processing in unconventional computing substrates
PhD thesis submitted	Not yet submitted as on 4-year PhD track

PhD defence date:	Expected 10/2025
Access to Full Text (Open Access)	Not available yet as on a 4-year PhD track.
PhD Thesis Abstract	
(Draft:) Guillaume Pourcel has worked on conceptors, a theoretical framework that bridges machine learning and dynamical systems. This work comprises of one co-authored on conceptor applied to motion modeling paper submitted to ICLR 2024 and authored by Guillaume Pourcel, Mirko Goldmann, Steven Abreu, and Miguel C. Soriano (available at https://openreview.net/forum?id=k65Nh7IV6X) and one extended abstract with an accompanied talk on a perspective of conceptor for unsupervised learning "Recurrent Neural Networks: from prediction to representation, a dynamical systems' perspective". Guillaume has also realized a secondment in Mallorca with ESR5 on conceptor for reservoir computing, where they designed an algorithm to deal with interpolation between time series and overcoming hardware deterioration. This last project will be submitted in April 2024. Currently, Guillaume Pourcel is generalizing the physical learning algorithm equilibrium propagation to deal with time series. This work has been accepted for a poster with the title “Forward prediction to enable backward temporal credit assignment via the neuronal least action principle”.	

ESR 3: MR ANAS SKALLI

Name	Anas Skalli
Host beneficiary:	Université de Franche Comté (UBFC)
Employment start date	1 October 2020
PhD Enrolment (University name)	Université de Franche Comté (UBFC)
PhD length	4 years
Main Supervisor:	Daniel Brunner (UBFC)
Industrial Supervisor	K. Eng (iniLabs)
PhD thesis title:	Advanced learning strategies for spatiotemporal photonic systems
PhD thesis submitted	Expected July 2024
PhD defence date:	Expected October 2024
Access to Full Text (Open Access)	Not available yet as on a 4-year PhD track. Thesis will be published in open access on the national repository for PhD reports in France: https://theses.hal.science/
PhD Thesis Abstract	
(Draft:)	

Artificial Neural Networks (ANNs) have become a ubiquitous technology; indeed, their flexibility allows them to excel in a wide range of tasks, ranging from medical diagnosis to language models. Unlike classical algorithms, these networks process information in parallel. Photonics, in particular, shows great promise as a platform for implementing ANNs in terms of scalability, speed, energy efficiency and parallel information processing.

Here, we experimentally demonstrate a high-performance, robust, autonomous, fully tunable, and scalable neural network of 1000+ discrete nodes based on a vertical cavity surface-emitting laser (VCSEL). Fully Autonomous photonic neural networks (PNNs) have been demonstrated, yet they remain scarce. In our approach, all parts of the neural network including input and output weights as well as nonlinearities, are fully realized in hardware using exclusively off the shelf components. Our optical neural network achieves high performance and a high classification bandwidth of 15KHz for the MNIST dataset with potential scalability towards the MHz range and beyond.

Finally, all learning is done online, using different hardware compatible learning strategies, which we benchmarked against each other regarding performance and energy cost. These learning strategies include techniques from reinforcement learning, evolutionary strategies and gradient estimation methods.

Our approach is highly relevant, fully parallel and scalable both in terms network size and depth as we have a clear avenue for using VCSELs in a deep PNN configuration. Lastly the inference bandwidth is also highly scalable due to a fast VCSEL response time (GHz range) without any significant increase in power consumption.

ESR 4: MR ENRICO PICCO

Name	Enrico Picco
Host beneficiary:	ULB
Employment start date	1 Sept 2020
PhD Enrolment (University name)	ULB
PhD length	4 years
Main Supervisor:	Serge Massar (ULB)
Industrial Mentor	Bert Offrein (IBM)
PhD thesis title:	Analog information processing inspired by the Cerebellum
PhD thesis submitted	Expected mid- 2024
PhD defence date:	Expected autumn 2024
Access to Full Text (Open Access)	Not available yet as on a 4-year PhD track.

PhD Thesis Abstract

Not available yet as on a 4-year PhD track.

ESR5: MR MIRKO GOLDMANN

Name	Mirko Goldmann
Host beneficiary:	IFISC (UIB - CSIC)
Employment start date:	16 October 2020
PhD Enrolment (University name)	Universitat de les Illes Balears (UIB)
PhD length	4 years
Main Supervisor:	Miguel C. Soriano (UIB), Claudio R. Mirasso (UIB), Ingo Fischer (CSIC)
Industrial Menor	K. Eng (iniLabs)
PhD thesis title:	Computing with dynamical system – from implementations towards novel concepts
PhD thesis submitted	Expected April 2024
PhD defence date:	Expected September 2024
Access to Full Text (Open Access)	Not available yet as on a 4-year PhD track.

PhD Thesis Abstract

(Draft)

This thesis investigates the computing capabilities of dynamical systems within the context of data-driven machine learning. Leveraging their inherent information processing, we aim to boost dynamical systems' efficiency and capability in solving supervised tasks. Here, we employ numerical simulations to model photonic hardware used for unconventional physical computing substrates. Additionally, we develop novel approaches, aiming to boost both, the optimization and generalization capacities of dynamical systems exemplified using generic recurrent neural networks.

First, we investigate the interplay of timescales in optoelectronic and photonic delay systems within the reservoir computing framework. By considering the input signal together with the reservoir's dynamics, we demonstrate the performance gains of oscillatory dynamics for chaotic time series processing, which were previously neglected for computing. Furthermore, we enhance prediction accuracy and inference rates by aligning input timescales with reservoir recurrence in a photonic delay system. In this last part, we underline the numerical results by verifying them with experimental data.

While highlighting the versatility of the reservoir computing paradigm, we demonstrate its underutilization in optimizing information processing related parameters. Comparing the performance of reservoir computing with a fully trained neural network approach, we show that fully trained systems with large set of adjustable parameters reach higher performance while requiring less nodes in complex tasks. To bridge the gap between reservoir computing and fully trained systems, we derive a regional training approach effectively trading performance against the number of trainable parameters. Relating these results towards unconventional physical computing, we argue the need to optimize large-scale parameter sets based on model-free optimization techniques. In this context, we propose a novel optimization method, by formalizing the optimization problem as a dynamical system. By exploiting oscillatory weight dynamics, a novel model-free optimization method raises a new perspective on the optimization process of physical substrates.

Finally, we discuss the generalization ability of dynamical systems by exploiting their continuous adaptability. We train dynamical systems on sparse data sets from a parametric family and afterward adapt it in the autoregressive mode toward new configurations generating unseen temporal patterns. Firstly, we leverage target model symmetry to learn from one time series and infer entire bifurcation diagrams. Secondly, we use the conceptor framework to learn from two time series and infer unseen intermediary dynamics. Finally, combining the conceptor framework with holistic optimization allows dynamical systems to generalize complex motion patterns.

In summary, this thesis establishes a connection among dynamical systems, machine learning, and unconventional computing, presenting novel methods to augment the computational prowess of dynamical systems. It demonstrates the computational capabilities of reservoir computing systems and introduces methodologies to extend their potential towards solving more complex tasks.

ESR6: MR IVAN BOIKOV

Name	Ivan Boikov
Host beneficiary:	Thales Research & Technology
Employment start date:	7 December 2020
PhD Enrolment (University name)	Paris-Saclay University
PhD length	3 years
Main Supervisor:	Alfredo de Rossi (Thales)
Academic Supervisor	Daniel Brunner (FEMTO-ST)
PhD thesis title:	Large scale autonomous all analogue photonic neural networks
PhD thesis submitted	14/03/2024
PhD defence date:	19/12/2024
Access to Full Text (Open Access)	**www.theses.fr/2023UPASP205** (On embargo until 19/12/2024) **www.theses.fr/s248409** (link to basic details of the PhD thesis)

PhD Thesis Abstract

A neural network is a brain-inspired approach to computing that allows us to solve problems that are difficult for traditional algorithmic methods. As a result, neural networks have found their place in many applications. Proposals for new tasks call for neural networks with high computational power, high speed and low latency, which has inspired research into neural networks in the optical domain.

This work considers a reservoir computer made by evanescently coupled optical microresonators. This architecture allows complex online processing of high-speed coherent optical signals and, in contrast to most studies in the literature, optical delay lines are suppressed, significantly reducing the chip footprint. The reservoir is assessed in a general sense by establishing a mathematical framework for its simulation and the evaluation of intrinsic properties, which applies to a wide range of semiconductors and types of resonators.

Its computing capability is demonstrated by predicting a physical system and data recovery from an optical fiber at a speed of tens of gigahertz. In this way, a direction for the development of large-scale integrated photonic networks is proposed.

This work also investigates the possibility of harnessing the recently demonstrated spiking nanolasers for the development of high-speed stochastic neural networks capable of sampling at hundreds of millions of samples per second.

ESR7: Mr Diego Arguello Ron

Name	Diego Arguello Ron
Host beneficiary:	Aston University
Employment start date	19 October 2020
PhD Enrolment (University name)	Aston University
PhD length	3 years
Main Supervisor:	Sergei Turitsyn (Aston)
Industrial Mentor	Bert Offrein (IBM)
PhD thesis title:	Implementation of neural networks and machine learning techniques using multi-core fiber platform
PhD thesis submitted	Not yet available
PhD defence date:	Not yet available
Access to Full Text (Open Access)	Not yet available
PhD Thesis Abstract	
Not yet available	

ESR8: Mr Daniel Hesslow

Name	Daniel Hesslow
Host beneficiary:	LightOn
Employment start date	1 Oct 2020
PhD Enrolment (University name)	UBFC
PhD length	3 years
Main Supervisor:	Laurent Daudet (LightOn); Peter Bienstmen (IMEC)
Accademic	Daniel Brunner (UBFC)

Supervisor	
PhD thesis title:	Solving large-scale inverse problems with optical computing
PhD thesis submitted	Expected Mid- 2024
PhD defence date:	Expected End- 2024
Access to Full Text (Open Access)	Not available yet.
PhD Thesis Abstract	
Not available yet.	

ESR9: Ms Sarah Masaad

Name	Sarah Masaad
Host beneficiary:	IMEC
Employment start date	26 October 2020
PhD Enrolment (University name)	Ghent University
PhD length	4 years
Main Supervisor:	Peter Bienstman (IMEC)
Academic Supervisor	H. Jaeger (Groningen)
PhD thesis title:	Photonic Reservoir Computing for Telecommunication Application
PhD thesis submitted	Expected Oct 2024
PhD defence date:	Expected Dec 2024
Access to Full Text (Open Access)	Not available yet as on a 4-year PhD track. https://www.photonics.intec.ugent.be/contact/people.asp?ID=540
PhD Thesis Abstract	
(Draft) Photonic reservoirs are machine learning based systems that boast energy efficiency and speediness. Thus they can be deployed as optical processors in fiber communication systems to aid or replace digital signal equalization. This thesis covers the use of a passive photonic reservoir to compensate for errors originating from the fiber, namely dispersion and self-phase modulation, those originating from the nonlinear response of the modulator, and those from self-coherent receivers. Experimental and simulation results show the successful mitigation and hence reduction in bit error rate.	

ESR10: MR BENEDIKT VETTELSCHOSS

Name	Benedikt Vettelschoss
Host beneficiary:	IMEC
Employment start date	1 March 2021
PhD Enrolment (University name)	UGent
PhD length	3 years
Main Supervisor:	J. Dambre (UGent); P. Bienstman (IMEC)
Industrial Mentor	L. Daudet (LightOn)
PhD thesis title:	Novel neuromorphic techniques for cell sorting applications
PhD thesis submitted	Not applicable due to ESR's resignation
PhD defence date:	Not applicable due to ESR's resignation
Access to Full Text (Open Access)	Not applicable due to ESR's resignation
PhD Thesis Abstract	
Not applicable	

ESR11: MR TIGERS JONUZI

Name	Tigers Jonuzi
Host beneficiary:	VLC PHOTONICS S.L.
Employment start date	1 September 2020
PhD Enrolment (University name)	Universitat de les Iles Baleares
PhD length	3 years
Main Supervisor:	Jose David Domenech Gomez (VLC Photonics)
Academic Supervisor	Miguel Cornelles Soriano (UIB)
PhD thesis title:	Integrated Photonics Ingredients for On-Chip Neuromorphic Computing
PhD thesis submitted	Expected 05/2024
PhD defence date:	Expected 07/2024
Access to Full Text (Open Access)	Not available yet. PHD thesis repository: The UIB has an institutional repository online portal where scientific and academic material produced at the

	university is digitally stored. In order to see a UIB PhD thesis, you need to search the repository. You can access it directly at the following address: repositori.uib.cat.
PhD Thesis Abstract	
(Draft:) This thesis delves into the realms of Integrated Photonics and Neuromorphic Network Architectures, investigating their principles and applications. The introductory chapters provide an overview of Integrated Photonics, covering topics such as light propagation in Photonic Integrated Circuits (PICs) and the functionalities of the basic tunable units. Neuromorphic Network Architectures are also explored, encompassing the Perceptron model, various Neural Network Schemes, and the integration of photonics into neural networks. The thesis then outlines its objectives and structure before delving into the methodology. The focus of the methodology lies in the study and development of actuation mechanisms for optical weight assignation, including Phase Shifters, Thermo-optic and Graphene actuators, as well as the integration of non-volatile actuation with Phase Change Materials. Additionally, the integration of Micro-electromechanical Systems (MEMS) into Silicon Photonics is examined. The core contributions of the research lie in the chapter on results, particularly exploring wavelength and time space multiplexing architectures. The exploration of wavelength dimensionality includes topics such as wavelength multiplexing and the generation of frequency combs. Furthermore, the thesis investigates time-multiplexed Reservoir Computing and introduces a Photonic Convolutional Accelerator, detailing its design and providing preliminary experimental setups and characterizations. In summary, this thesis advances the understanding and application of Integrated Photonics and Neuromorphic Network Architectures, with significant contributions in exploring multiplexing architectures for enhanced computing and information processing systems.	

ESR12: MR ALESSANDRO LUPO

Name	Alessandro Lupo
Host beneficiary:	ULB
Employment start date	1 Sept 2020
PhD Enrolment (University name)	ULB
PhD length	4 years
Main Supervisor:	Serge Massar (ULB)
Industrial Mentor	Bert Offrein (IBM)
PhD thesis title:	Temporary title: Optical Reservoir Computing based on frequency multiplexing
PhD thesis submitted	Expected May 2024
PhD defence date:	Expected July 2024
Access to Full Text (Open Access)	Not available yet as on a 4-year PhD track.

PhD Thesis Abstract

(Draft:)

We live in the era of big data: by 2025, the world will have created 150 zettabytes of information. The predominant tools for processing this data are Artificial Neural Networks (ANNs). Due to its architecture, a traditional Von Neumann processor is not efficient in executing ANN algorithms. Moreover, the miniaturization of electronic components may soon reach a physical limit. For these reasons, novel schemes for computation are required. In this thesis we explore the possibility of executing randomized ANN algorithms on photonic systems exploiting frequency multiplexing to encode neurons. We present experimental schemes that exploits either phase modulation of light or Kerr nonlinearity in fiber to process information. We prove the possibility of executing parallel operations on the same hardware, potentially in a fully analog fashion, thus avoiding the costs of digital-to-analog and analog-to-digital conversion.

ESR13: MR LONG HOANG NGUYEN

Name	Long Hoang Nguyen
Host beneficiary:	Aston University
PhD Enrolment (University name)	Aston University
PhD length (*)	3 years
Main Supervisor:	Stylianos Sygletos (Aston)
Industrial Mentor	Bert Offrein (IBM)
PhD thesis title:	Digital signal processing techniques for optical devices using nonlinear optical processes
PhD thesis submitted	Expected September 2024
PhD defence date:	Expected November 2024
Access to Full Text (Open Access)	https://research.aston.ac.uk/en/studentTheses/

PhD Thesis Abstract

(Draft:)

Optical devices using nonlinear optical processes, such as optical phase conjugators (OPCs) and fibre optical parametric amplifiers (FOPAs), are promising candidates for the future of fibre-optic networks by offering transformative capabilities in terms of signal quality, transmission distances, and network efficiency. OPCs enables the all-optical signal distortion compensation capability by mitigating the detrimental effects of nonlinearities, dispersion, and other impairments in the optical transmission. FOPAs introduces advanced amplification mechanism leveraging the nonlinear properties of optical fibres, and is crucial for extending transmission distances, and enabling flexible wavelength division multiplexing (WDM) schemes in the next-generation optical networks.

Stimulated Brillouin scattering (SBS), however, remains a fundamental challenge for these devices and a commonly used solution strategy involves broadening the linewidth of the pump

source, effectively reducing the power spectral density integrated over the Brillouin bandwidth. This is often achieved by introducing pump-phase modulation driven by electrical signals, such as a combination of multiple radiofrequency (RF) tones. However, this phase modulation is transferred to the output signal, thereby deteriorating signal quality in optical coherent systems, and the phase distortion interacts with fibre dispersion in subsequent fibre spans, leading to phase and amplitude distortions observed in the output signal detected at the receiver.

The dissertation explores novel digital signal processing (DSP) algorithms, encompassing both parametric and non-parametric approaches, aimed at predicting and compensating for dithering-induced distortion. The proposed algorithms can effectively remove the distortion in the three-tone dithering modulation scheme and at least double the transmission reach in others utilising more RF tones. This class of DSP techniques plays a crucial role in preserving the advantages of OPCs and FOPAs without compromising signal quality for seamless integration of them into advanced optical networks.

ESR14: MR LUCAS TALANDIER

Name	Lucas Talandier
Host beneficiary:	CSIC
Employment start date:	1 November 2020
PhD Enrolment (University name)	Universitat de les Illes Balears (UIB)
PhD length	3 years plus 1 year extension granted
Main Supervisor:	Apostolos Argyris (CSIC), Ingo Fischer (CSIC),
Industrial Supervisor	David Domenech (VLC Photonics)
PhD thesis title:	High-speed non-algorithmic analogue photonic computing with applications in telecom and datacom
PhD thesis submitted	Expected July- 2024
PhD defence date:	Expected October 2024
Access to Full Text (Open Access)	Not available yet as on a -4th year extension

PhD Thesis Abstract

(Draft:)

The work of this PhD thesis includes a detailed exploration of the possibilities for post-processing optical communication signals by using photonic approaches based on machine learning techniques and specifically on reservoir computing with photonic systems. The impact of phase-dependent transformations is explored, which offer a clear advantage over current techniques that consider amplitude-only encoding of telecom signals. The approach investigated in this thesis explores the influence of cavity length in photonic time delay reservoir computing (TDRC), particularly focusing on systems using a pair of coupled semiconductor lasers. This study demonstrates that using a short reservoir cavity, in contrast to the usual approaches of long-cavity reservoirs, introduces a radical enhancement in the system's efficiency.

ESR15: MR ELGER VLIEG

Name	Elger Vlieg
Host beneficiary:	IBM Research
Employment start date	1 Feb 2021
PhD Enrolment (University name)	UGent
PhD length	4 years
Main Supervisor:	Bert Jan Offrein (IBM) , Folkert Horst (IBM)
Academic Supervisor	Peter Bienstman (Ugent)
PhD thesis title:	Tentative title: Photonic synaptic processor
PhD thesis submitted	Expected end 2024
PhD defence date:	Expected January 2025
Access to Full Text (Open Access)	Not available yet as on a 4-year PhD track.
PhD Thesis Abstract	
Not available as on a 4-year PhD track.	