

A scalable and fully tuneable VCSEL-based neural network

Anas Skalli^{1*}, Mirko Goldmann², Xavier Porte³, Nasibeh Haghighi⁴, Stephan Reitzenstein⁴, James A. Lott⁴, and Daniel Brunner¹

1. Institut FEMTO-ST, Université Bourgogne Franche-Comté, CNRS UMR6174, 15B Avenue des Montboucons Besançon, France
2. Instituto de Física Interdisciplinar y Sistemas Complejos, IFISC (UIB-CSIC), Campus UIB, E-07122 Palma de Mallorca, Spain
3. Institute of Photonics, Department of Physics, University of Strathclyde, 99 George str., Glasgow G1 1RD, UK
4. Institut für Festkörperphysik, Technische Universität Berlin, Hardenbergstraße 36, 10623 Berlin, Germany

Abstract. We experimentally demonstrate an autonomous, fully tuneable and scalable neural network of 350+ parallel nodes based on a large area, multimode semiconductor laser. We implement online learning strategies based on reinforcement learning. Our system achieves high performance and a high classification bandwidth of 15KHz for the MNIST dataset. Our approach is highly scalable both in terms of classification bandwidth and neural network size.

The versatility of Artificial Neural Networks (ANNs) has made them a ubiquitous technology. Whether it's medical diagnosis or language models, ANNs are capable of excelling in a wide range of tasks. By processing information in parallel, they stand apart from classical algorithms. Photonics holds tremendous promise as a platform for implementing ANNs in terms of scalability, speed, energy efficiency, and parallel information processing [1]. In [2], we physically implemented the first fully autonomous PNN (photonic neural network), using spatially multiplexed modes of an injection locked large area vertical cavity surface emitting laser (LA-VCSEL). All components of our PNN, including learning are fully realized in hardware using off-the-shelf, commercially available, low energy consumption components, while still achieving >98% accuracy in 6-bit header recognition tasks and promising initial results for the MNIST hand written digit recognition dataset, where we achieve 90% accuracy on average. Crucially, our system performs classification at a high bandwidth of 15 kHz, which is not limited by the LA-VCSEL (GHz bandwidth) and could potentially increase towards the MHz range. The PNN presented here was first implemented in [2,3]. Whereas previously it followed the reservoir computing (RC) concept, where input and internal weights are fixed and only the output weights are trained.

We now present an improved version of the setup where all connections in the PNN can be trained yielding therefore a highly tuneable network. The experimental scheme is shown in Fig. 1.

Input images $\mathbf{u}$ displayed on a digital micromirror device (DMD_a) are passed through a phase mask displayed on a spatial light modulator (SLM) which encodes the input weights $\mathbf{W}^{\text{in}}$. The phase modulated input is injected onto the LA-VCSEL through a multimode fiber (MMF) which passively implements a random linear mixing $\mathbf{W}^{\text{rand}}$. The VCSEL then transforms the injected information non-linearly yielding the perturbed mode profile $\mathbf{x}$. The final part of the PNN is its output layer. The VCSEL's surface is imaged onto DMD_b, whose pixels can flip between two positions, for one of which it reflects light onto the photodetector (DET), giving us Boolean output weights $\mathbf{W}^{\text{out}}$. 350+ nodes are implemented fully in parallel; the output of the PNN $\mathbf{y}$ is the optical power detected at DET. $\mathbf{W}^{\text{out}}$ and $\mathbf{W}^{\text{in}}$ are trained via iterative optimization based on evolutionary search algorithms or gradient descent using gradient estimation methods from reinforcement learning. Higher output weight resolutions can be achieved with higher imaging magnifications onto DMD_b. Additionally negative output weights can be achieved via recording the output of the PNN twice and implementing an electronic subtraction.

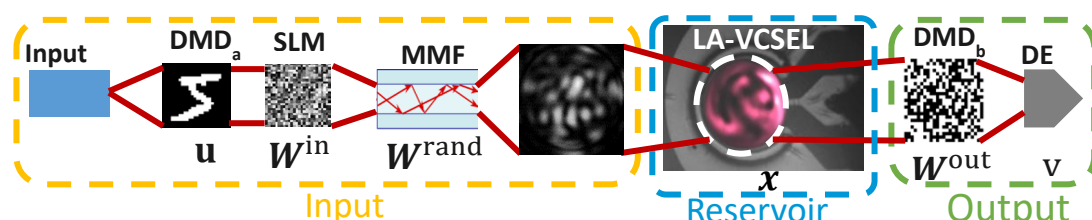


Fig. 1. Working principle of our experimental photonic neural network

* Corresponding author: anas.skalli@femto-st.fr

Fig. 2 shows preliminary classification performance for the MNIST task using Boolean weights (BOOL), and trinary weights (3val -1,0, +1) reaching an average performance of 90% for trinary weights which have a significant positive impact on performance. In addition, we conducted a long-term stability analysis in Fig. 3, over a period of 10 hours, showing little to no degradation in performance or drift. Moreover, the average cross correlation between different outputs over the 10 hours was 98%. We also studied the impact of different learning strategies and physical parameters of our PNN (injection power and wavelength, bias current, etc...) on its performance for classification tasks as well as how they impacted other dynamical properties such as consistency and dimensionality, showing a promising consistency of 99%

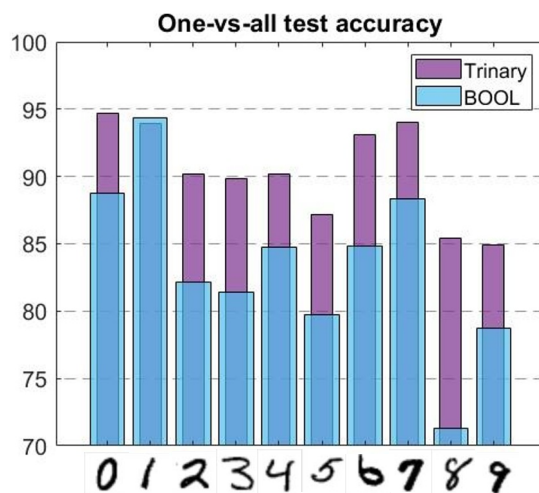


Fig. 2. One-vs-all test accuracy for the hand written MNIST dataset using Boolean (BOOL) and trinary (-1,0, +1) output weights.

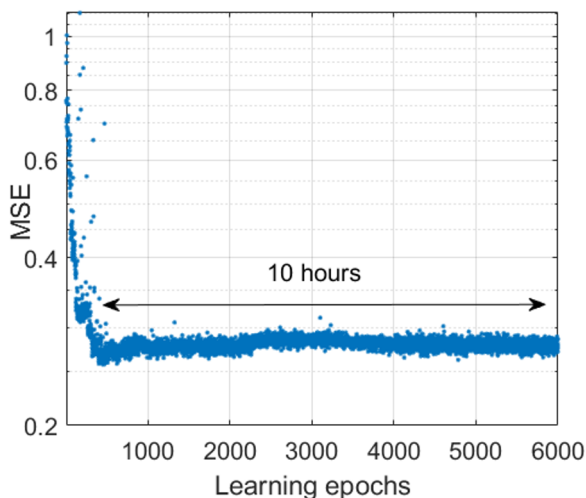


Fig. 3. Long term stability measurement showing minimal drift in performance over 10 hours showcasing the stability of our photonic neural network

such as header recognition, XOR, and digital-to-analog conversion. Additionally, we have achieved promising results in the challenging MNIST dataset with a classification bandwidth of 15kHz. Our fully parallel and scalable approach, utilizing VCSELs, offers a clear path for developing deep PNN configurations. Finally, owing to a fast VCSEL response time, our approach allows us to increase inference bandwidth without significant increases to power consumption.

References

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In summary, our VCSEL-based PNN, comprised of over 350 neurons, has demonstrated remarkable long-term stability and exceptional performance in various tasks,