

Processing information using recurrent neural networks in silicon photonics

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Abstract

We will discuss how integrated photonic reservoir computing is a promising approach for solving a number of problems in telecommunications, e.g. non-linear dispersion compensation. We have shown experimentally that using a reservoir consisting of only 20 nodes can achieve sub-FEC error performance on on-off keying (OOK) signals at 32 Gbaud/s in real time. Such a neuromorphic approach has the potential for being a high-speed low-power alternative for traditional electronic DSP. We also showed in simulations that the scheme can be extended from simple modulation formats like OOK to complex coherent formats. Finally, we discuss progress towards equalisation of WDM signals.

Index Terms

reservoir computing, equalisation, OOK, QAM, WDM

I. INTRODUCTION

The continuous growth in global data traffic places increasing demands on the performance, scalability, and energy efficiency of optical communication systems. As symbol rates and transmission distances increase, optical signals become progressively more distorted by linear impairments such as chromatic dispersion and by nonlinear effects originating from the Kerr nonlinearity in optical fibres. While advanced digital signal processing (DSP) techniques can compensate for these impairments, their power consumption, latency, and scaling complexity pose significant challenges for future high-capacity systems.

Photonic computing has emerged as a promising alternative approach, offering the potential for ultra-high bandwidth processing with reduced energy consumption by exploiting the intrinsic speed of optical hardware. Within this broader field, photonic reservoir computing (PRC) has attracted growing interest as a particularly robust and hardware-efficient paradigm. Reservoir computing leverages the complex dynamics of a fixed nonlinear system, referred to as the reservoir, while restricting training to a simple linear readout layer. This separation between physical dynamics and training complexity makes reservoir computing well suited for implementation in integrated photonic platforms.

We review our recent experimental work on the application of integrated photonic reservoir computing to optical signal equalisation. We first demonstrate equalisation of intensity-modulated on-off keying (OOK) signals, establishing photonic reservoir computing as a viable real-time equalisation technique [1]. We then switch to coherently modulated signals, where amplitude and phase information must be processed jointly [5]. Finally, we present a first experimental step towards wavelength-division multiplexed (WDM) signal equalisation using a single photonic reservoir and a single set of trained readout weights [2]. Together, these results highlight the potential of photonic reservoir computing as a scalable analogue signal processing front-end for next-generation optical communication systems.

II. PHOTONIC RESERVOIR COMPUTING FOR OPTICAL COMMUNICATIONS

Reservoir computing [3], [4] is a computational framework derived from recurrent neural networks in which the recurrent structure is left untrained and only the output layer is optimised. The reservoir itself is a dynamical system with nonlinear response and fading memory, enabling it to map temporal input signals into a high-dimensional feature space. Training is limited to determining a linear combination of the reservoir states that best approximates a desired output, typically using simple linear regression techniques.

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This approach offers several advantages for hardware implementations. Since the internal connections of the reservoir are fixed, the system is robust to fabrication imperfections and parameter variations. Moreover, training complexity is significantly reduced compared to fully trainable neural networks, making reservoir computing attractive for real-time and resource-constrained applications.

Photonic reservoir computing comes in two variants: time-multiplexed and spatially multiplexed [6]. In the latter case, each node is physically present, e.g. as optical components in an integrated photonics chip. These integrated implementations typically consist of passive waveguide networks with multiple interconnected nodes, where signals propagate along paths with different delays and phases. Nonlinearity is often introduced through square-law photodetection at the readout stage, although all-optical nonlinearities may also be employed.

Integrated photonic reservoirs offer several key advantages over fibre-based or free-space implementations, including compactness, mechanical stability, and compatibility with large-scale integration. Furthermore, photonic reservoirs naturally support extremely high bandwidths, making them well suited for processing optical communication signals directly in the analogue domain.

One important such task is signal equalisation, which is fundamentally a temporal processing task requiring both memory and nonlinear transformation capabilities. Linear equalisation techniques can mitigate inter-symbol interference caused by dispersion, but struggle with nonlinear impairments such as self-phase modulation. Reservoir computing provides a natural solution by combining fading memory with nonlinear mixing, enabling it to approximate complex inverse channel dynamics.

In contrast to conventional electronics DSP-based equalisation, photonic reservoir computing operates directly on the optical signal, reducing the need for high-speed analogue-to-digital conversion and intensive digital processing. This makes PRC an attractive candidate for low-latency, energy-efficient signal equalisation in future optical networks.

III. EQUALISATION OF INTENSITY-MODULATED OOK SIGNALS

As a first example, we will discuss experiments to equalise impairments in high-speed OOK Transmission. Despite its conceptual simplicity, on-off keying remains widely used in cost-sensitive optical links. At high symbol rates and elevated launch powers however, OOK signals suffer from severe eye closure due to chromatic dispersion and fibre nonlinearities. These effects introduce memory and nonlinear distortion that cannot be fully compensated using simple linear filters.

To address this challenge, we employed an integrated photonic recurrent reservoir based on a passive interferometric waveguide network. Additionally, we implement the readout stage also in an all-optical fashion, by taking the linear combination in the optical domain, using complex-valued weights. This allows the inference to happen in real-time at the line rate of the optical data stream, without the need for high-speed electronics.

The reservoir is implemented in SiN consists of multiple interconnected nodes arranged in a two-dimensional topology (the so-called four-port architecture) (Fig. 1), where each node has as many inputs as outputs, in order to prevent radiation losses upon combining waveguides. The input OOK signal is injected directly into the reservoir, where it undergoes complex interference and temporal mixing.

In our experimental setup, a high-speed OOK signal is transmitted through a dispersive and nonlinear fibre link before being processed by the photonic reservoir. The readout weights were trained using an evolutionary algorithm, with the hardware in the loop in order to account for fabrication imperfections. Experimental results in [1] show a substantial reduction in bit error rate compared to a linear feedforward equaliser baseline, demonstrating effective compensation of both linear and nonlinear impairments.

The OOK equalisation experiments demonstrate that photonic reservoir computing can perform real-time nonlinear signal processing without resorting to power-hungry DSP. Importantly, the reservoir operates passively, with no need for active tuning of internal parameters, highlighting its robustness and suitability for practical deployment.

IV. EQUALISATION OF COHERENTLY MODULATED SIGNALS

Next, we turn our attention to coherent modulation formats such as QPSK and QAM. They enable high spectral efficiency but introduce additional signal processing challenges. Equalisation must account for amplitude and phase distortions, polarization effects, frequency offsets, and phase noise. Conventional coherent receivers rely on complex DSP pipelines to address these impairments.

In our proposed receiver architecture, the photonic reservoir replaces the most time-consuming DSP blocks responsible for nonlinear equalisation and transceiver impairment compensation. Residual tasks such as frequency offset correction and carrier phase recovery remain in the digital domain, resulting in a hybrid photonic–electronic processing chain.

Experimental demonstrations using 4-QAM and 16-QAM signals at 28 Gbaud show that the reservoir-based equaliser achieves bit error rates comparable to those obtained with conventional DSP-based solutions (Fig. 2), without the need for sampling twice per symbol. Important to note is that crucial to these results is the joint optimisation of the entire pipeline, i.e. covering both the photonic processing and the remaining DSP.

These results confirm that photonic reservoirs can effectively process complex-valued signals and handle the increased impairment complexity of coherent systems.

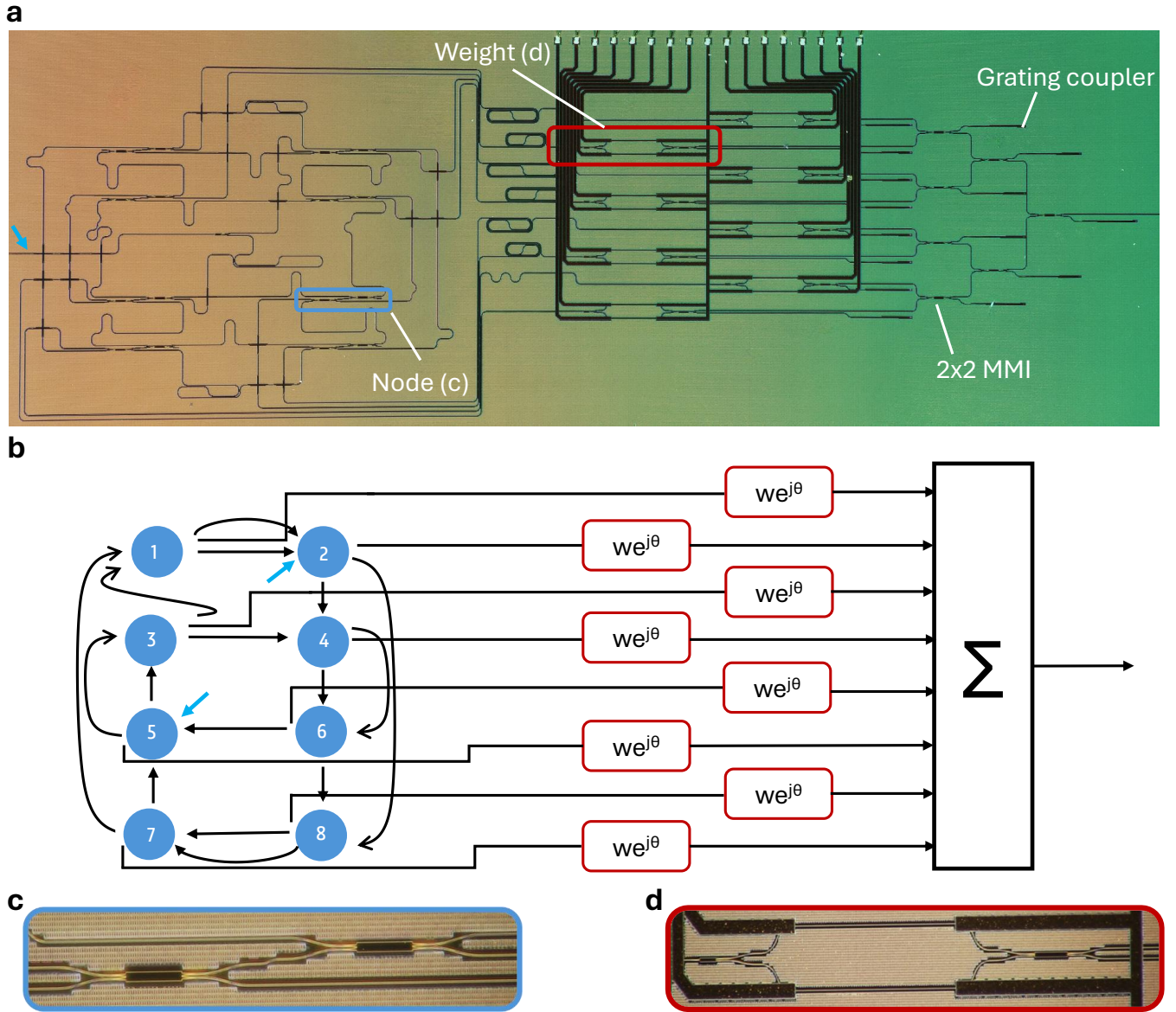


Fig. 1. **Design of photonic integrated reservoir** (a) Microscope image of the chip design with a blue rectangle showing a node, and a red rectangle showing a weight implemented as an MZI with heaters. (b) Schematic representation of the chip. Blue circles indicate nodes, and arrows indicate the propagation direction of the light. Note that the detector is off-chip (c) Close-up image of a node composed of two 2x2 MMIs. (d) Close-up image of an MZI with heaters.

V. TOWARDS EQUALISATION OF WDM SIGNALS

Scaling optical communication systems to ever higher capacities requires efficient wavelength-division multiplexing. For photonic reservoir computing to be viable in this context, it must process multiple wavelength channels without excessive duplication of hardware or control complexity. In practice, this means using a single photonic reservoir and a single set of readout weights to equalise signals at different wavelengths.

In order to achieve this, we incorporated multiple wavelengths into the training process, so that the readout layer learns to generalise across wavelength-dependent phase variations within the reservoir. As a side benefit, the system also became more robust to temperature-induced wavelength shifts.

Using OOK signals at multiple ITU-T grid wavelengths, we demonstrated effective nonlinear equalisation across at least three channels using identical readout weights. Bit error rates remained well below relevant forward error correction thresholds, even at high launch powers inducing strong nonlinear distortion (Fig. 3).

While these experiments do not yet include simultaneous multi-wavelength propagation with cross-phase modulation, they constitute an important first step towards scalable WDM-compatible photonic reservoir computing. Future work will address

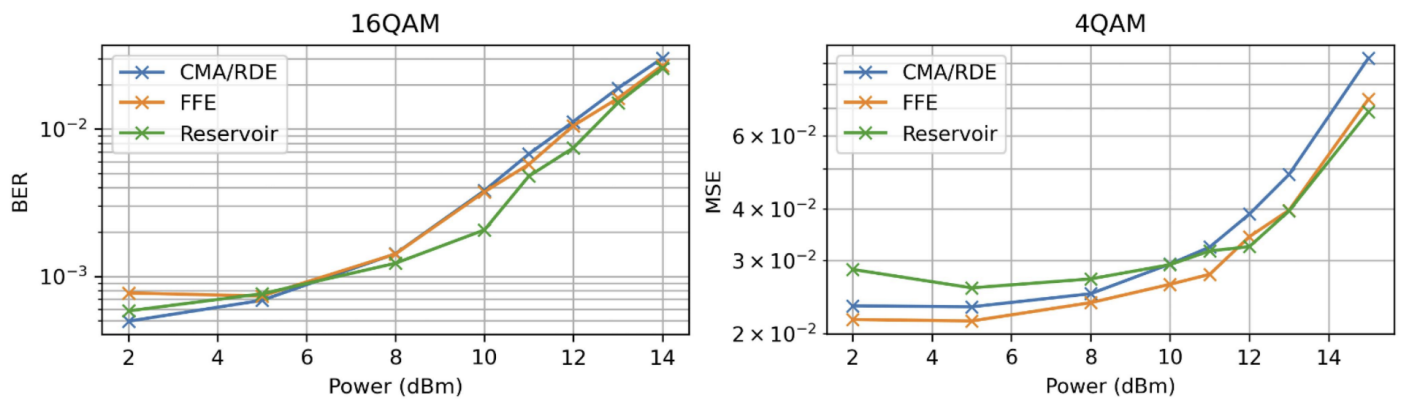


Fig. 2. Equalization results over a range of transmission powers from RC system (green) benchmarked against two different full DSP pipelines equalized using respectively CMA/RDE (Constant Modulus Algorithm/Radius Directed Equalisation) (blue) and FFE (Feedforward equalisation) (orange). BER results are reported for 16-QAM (left) and MSE results are reported for 4-QAM (right).

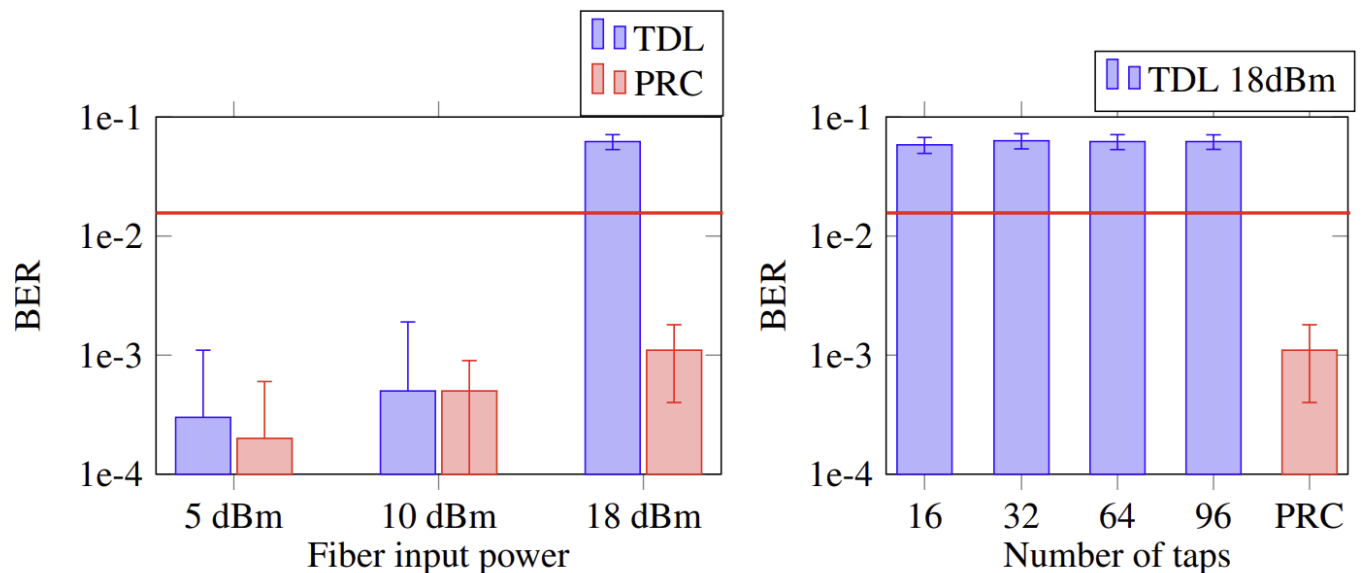


Fig. 3. Average BER, with error bars indicating standard deviation, over the cross validation iterations for a tapped delay line (TDL), trained and tested for one wavelength (1552.524 nm) in comparison with worst performing single-readout photonic reservoir computing (PRC) wavelength. (Left) For various levels of input power. (Right) For different number of tapped delay line taps at 18 dBm input power. The horizontal red line illustrates the relevant FEC limit.

true WDM transmission scenarios and investigate the impact of inter-channel nonlinearities.

VI. CONCLUSION AND OUTLOOK

We presented a unified overview of our work on photonic reservoir computing for optical signal equalisation. Starting from intensity-modulated OOK signals, we demonstrated real-time nonlinear equalisation using integrated photonic reservoirs. We then extended the approach to coherently modulated signals, showing that photonic reservoirs can process amplitude and phase information and replace multiple DSP blocks in coherent receivers. Finally, we presented initial experimental results indicating that photonic reservoir computing can scale to wavelength-division multiplexed systems using a single set of trained readout weights.

Looking forward, improved programmability and scaling to higher modulation orders and channel counts will be key research directions. Photonic reservoir computing offers a compelling pathway towards low-latency, energy-efficient signal processing in future optical communication networks, complementing and potentially offloading conventional digital signal processing techniques.

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