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Experimental Demonstration of 4-Port Photonic Reservoir Computing for Equalization of 4 and16 QAM signals

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Abstract *We experimentally demonstrate equalization of coherently modulated signals at 28Gbaud using a passive, 16-node, integrated, 4-port photonic reservoir. The reservoir replaces computationally expensive DSP procedures for passive/active equalization and integrates with other DSP blocks achieving BERs on-par with legacy DSP for 4 and 16QAM signals.*

Introduction

Coherent communication has been a key enabler in increasing transmission throughput without taxing on the limited bandwidth of electronic interfaces, since it allows multilevel modulation over two orthogonal quadratures. However, the computationally expensive and power-hungry digital signal processing (DSP) procedures that are required post-detection remain hindering for high baud rate implementations and/or for mass deployment of coherent transponders in short and mid-reach systems [1]. Alternative solutions to standard DSP methods, like analogue-based solutions, can circumvent these high sampling rates and computational requirements. In particular, optical signal processing techniques are an attractive solution since their computational bandwidths match the transmission bandwidths. In this paper, we demonstrate the use of an integrated photonic network that replaces digitally implemented equalizers for chromatic dispersion and transceiver impairments. Offloading these steps, which normally operate at twice the baud rate, into the optical domain considerably reduces the computational complexity of the pipeline and the bandwidth of the electronics.

Photonic Reservoir Computing

Integrated photonics offers the capability of miniaturizing and integrating various photonic components onto a compact chip which facilitates the generation, modulation, processing, and detection of light with minimal footprint [2]. By utilizing this technology, various approaches, including those based on machine learning, are currently explored to enable light-based computing in compact circuits. This allows using light's large bandwidths, low-loss channels, and multiplexing capabilities for performing computational tasks.

To this end, a prominent framework, known as reservoir computing (RC), has been successfully used for computing with light in a plethora of machine learning and signal processing applications [3],[4]. An RC network consists of a number of nodes linked with weighted interconnects, similar to a recurrent neural network. However, the network's inner connections are random and untrained. Only the output weights, in what is known as the readout, are trainable. This offers an efficient way to construct neural networks in physical hardware where manipulating internal weights is either expensive or inherently infeasible.

Our implementation of an integrated photonic reservoir, which we term the 4-port architecture [5], is based on a silicon nitride platform and utilizes 3x3 multimode-interferometers as nodes. As seen in Fig 1, two of a node's input ports come from other reservoir nodes and two of its output ports connect to other nodes. The third input port allows injecting an external signal into the reservoir and the third output port leads to the readout where complex-valued trainable weights are implemented. The fixed weights inside the reservoir originate from the waveguide interconnects which induce phase and amplitude modulation on the propagating signals. Due to inherent fabrication imperfections, such as sidewall roughness, each fabricated reservoir has a unique, yet fixed, set of internal phase weights.

Fig 1 also depicts two methods for implementing the readout. In the parallel readout, shown in red, the readout signals from the reservoir are directed to integrated and optically implemented weights, followed by an integrated summation tree. Here, optical weights are iteratively adjusted during the training phase until the weighted and summed output detected by the receiver closely resembles the target signal. Then the trained weights are used in the testing phase.

If a parallel readout cannot be implemented, a

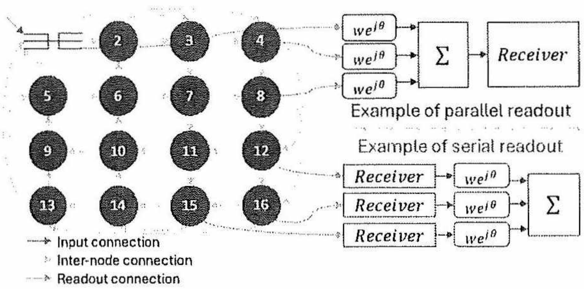

Fig. 1: 16-node reservoir with 2 possible readout schemes. Nodes are numbered vertices, with the exception of node 1, shown as an abstracted 3x3 multimode interferometer.

serial readout, shown in blue, is an alternative for proof-of-concept lab experiments. Here, each readout channel is measured separately and sequentially and is stored offline for weight computations. Note that the entire reservoir would follow one readout scheme, however they are both depicted on the same figure for conciseness.

The serial readout is normally not preferred since measuring nodes sequentially adds processing complexity (as will be seen later) and prohibits online utilization of the reservoir. However, it can be used as a temporary fallback to bypass issues associated with excessive optical losses. This was the case with the generation of the 4-port reservoir used in this experiment, where around 8 dB losses per coupler are incurred when coupling in and out of the reservoir. Additional component losses are also incurred. While these losses are significantly reduced in newer generations of the reservoir chip, they were prohibitive in this experiment from utilizing the parallel readout scheme. This is because utilizing the integrated readout will accumulate optical combining losses on top of those already incurred, which would place the detected signals below the noise floor of the receiver.

Extensive simulations and experiments have demonstrated the versatility of this architecture in tackling applications in fiber-optic communication systems. For example, experimental equalization was demonstrated in [6] for intensity modulated and direct detected signals. In [7], the same set of readout weights was experimentally shown to equalize signals of multiple wavelengths, being a first step towards the applicability of this reservoir in wavelength division multiplexed systems. In this paper, we experimentally show that the 4-port reservoir can successfully equalize 4 and 16 QAM signals in the presence of chromatic dispersion and transceiver impairments, matching the performance of legacy DSP.

System and Results

The experimental setup is shown in Figure 2. On the transmitter's side, a dual polarization IQ modulator was used to modulate a continuous wave (CW) laser emitting at 1550 nm by a randomly generated data stream. The data stream was composed of either 4 or 16 QAM symbols pulse shaped using a root raised cosine filter with a roll-off of 0.2 and transmitted at 28 Gbaud.

The output of the transmitter was amplified by Amplifier 1 to 23 dBm, and then attenuated by a variable optical attenuator that controls the desired input power into the fiber. This setup allowed sweeping the fiber's input power without changing the noise profile of the amplifier. The signals traversed 20 km of standard single mode fiber. As discussed in the previous section, significant losses were incurred in that generation of reservoir, ranging between 35 dB and 50 dB per node, and thus further amplification before detection was needed. This amplification is divided between Amplifier 2 (before the reservoir) and Amplifier 3 (after the reservoir) such that the input power to the receiver was maintained at 0 dBm. All amplifiers were erbium-doped fiber amplifiers.

As a benchmark, the reservoir was replaced by an attenuator that introduced a 35 dB loss. Measurements on the reservoir and the benchmark were done consecutively, by connecting either the attenuator or the reservoir to the setup

The receiver is a dual polarization coherent receiver with a transimpedance amplifier. The detected signals are sampled at the Real-Time Oscilloscope (RTO) at 64 Gsamples/sec and then stored on a computer for offline processing.

Despite the dual polarization setup, only one polarization was transmitted, since the grating couplers and waveguides on the chip are very lossy for TM waves. Therefore, the data stream was loaded with zeros on the IQ arms of the Y (or TM) polarization. Since the modulator was biased at the null point, the carrier was also supressed, leaving the output of the Y polarization arm on the transmitter's side negligible.

Due to polarization rotations, a polarization controller is used to align the arriving signal with the TE polarization, maximizing the output power from the reservoir. At the receiver's end, the signal also arrives with a random state of polarization due to rotations, and the signal is detected on both polarization branches of the receiver.

The DSP pipeline [8] for the benchmark setup is shown in Fig 3a. The signals are equalized for the incurred dispersion using a chromatic dispersion compensating (CDC) filter and for transceiver imperfections by a 17-tap trainable filter deploying the CMA/RDE algorithm. Traditionally the CMA/RDE would perform linear equalization

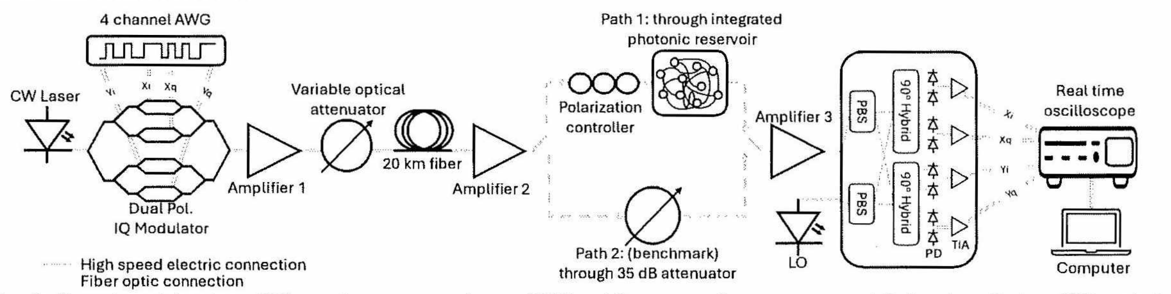

Fig. 2: Experimental setup. CW: continuous wave laser, AWG: arbitrary waveform generator, LO: local oscillator, PBS: polarization beam splitter, PD: photodiode, TIA: transimpedance amplifier.

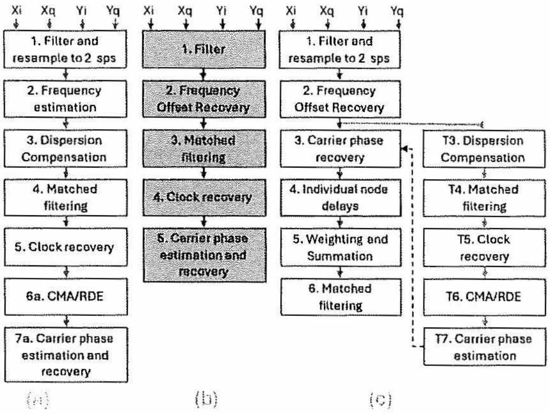

Fig. 3: DSP for (a) benchmark (b) photonic RC with parallel readout, (c) photonic RC with serial readout.

and polarization demultiplexing, however since only one polarization was transmitted, it is reduced to a blind adaptive equalizer. Both CDC and adaptive equalization procedures are replaced by the photonic RC, which offers considerable speed and power advantages since they happen in one shot, at the speed of transmission, and bypass the need for complex-valued digital operations at twice the baud rate.

DSP procedures also compensate for time-varying issues, including the frequency offset between the CW and LO, the phase and frequency offsets of the RTO sampling clock, and the phase offset of the CW. These time-varying issues must be tracked and are mostly artefacts that happen after the receiving process itself.

While the photonic reservoir supports the migration of expensive and optically implementable equalization blocks to the photonic realm, DSP procedures correcting for the aforementioned variable errors are still necessary. This results in an opto-electronic cointegrated solution with low DSP requirements. The pipeline in red in Fig 3b shows the remaining DSP procedures for a photonic reservoir with a parallel readout.

For a reservoir with serial readout, the sequential measurement of the readout nodes requires special handling as shown in Fig 3c. In this case, all time-varying issues need to be compensated for each node individually, since each node would have incurred different values for these issues. However, DSP procedures for these compensations are devised for input signals of certain criteria. For example, clock recovery algorithms require clear transitions between symbols, and as such is implemented after CDC. Naturally, with readout signals that are formed from dispersed signals that interfere within the reservoir, clock recovery is very challenging. As such, this step is omitted from the pipeline with negligible penalty.

More nuanced is carrier phase estimation by blind phase search (BPS), which requires having an equalized signal before the algorithm is applied and as such is normally the last block in the chain. However, with a serial readout, each node would have different time varying phase rotations and thus must be compensated for this before the nodes are summed. To bypass this issue, a temporary chain of DSP blocks, greyed in Fig 3c, is implemented, where the nodes are dispersion compensated and then equalized through an adaptive equalizer that undoes the reservoir mixing. A phase offset array is obtained using BPS and used to compensate unequalised node data.

The sequential measurement of nodes also means that their temporal alignment with respect to each other is lost and is adjusted offline. We also stress again that the entire pipeline of Fig 3c is only needed for the temporary fallback readout scheme, and not for the ultimate parallel scheme that should be facilitated by our next chip generation, which will utilize pipeline 3b.

Figure 4 shows BERs for 16 QAM and MSEs for 4 QAM (since BER is negligible) obtained from the reservoir with a serial readout scheme. The training set is composed of 20,000 symbols, while the results reported are for a different testing set of 75,000 symbols. The results are benchmarked against the DSP pipeline shown in Fig 3a. The minor improvements from the reservoir are attributed to the training method that is data-aided, as opposed to the benchmark's blind optimization. The results show the applicability of the same reservoir in a range of operational conditions: high and low modulation formats, as well as linear and nonlinear fiber input powers. Results for the photonic RC show same or better performance compared to its digital counterparts achieved at transmission speed, thus alleviating computational bottlenecks.

Conclusions

We experimentally demonstrate the use an integrated photonic reservoir for the equalization of 4 and 16 QAM signals at 28 Gbaud, replacing computationally expensive passive and active procedures in a DSP pipeline. Results match legacy DSP while performing equalization at the speed of transmission and bypassing the need for computations at twice the baud rate.

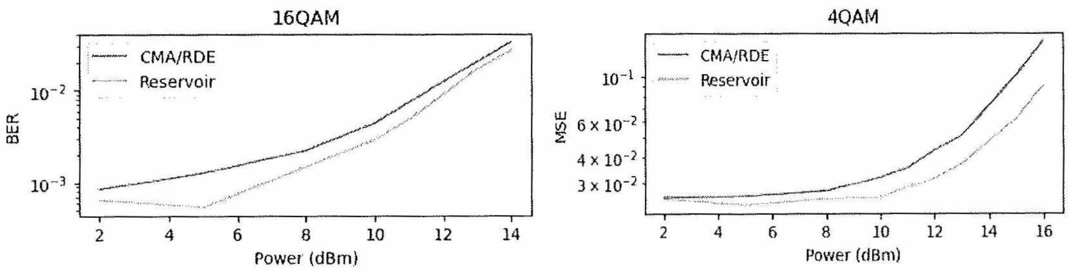

Fig 4. Testing results showing BER for 16 QAM and MSE for 4 QAM for a range of fiber input powers

Acknowledgements

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David Sanchez | iPronics S.L. | Spain
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04:30 pm

M3G.3: Experimental Demonstration of 4-Port Photonic Reservoir Computin and16 QAM signals

Sarah Masaad | Belgium
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Peter Bienstman | Belgium

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equalization and integrates with other DSP blocks achieving BERs on-par with legac

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M3G.4: Digital-analog Hybrid Matrix Multiplication Processor for Optical Ne

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04:15 pm

M3G.2: Experimental Investigation of a Neuromorphic Accelerator based on Reconfigurable Photonic Chip for High-Speed Image Processing

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04:30 pm

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