European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Machine Learning and Neuromorphic Computing Approaches for the mitigation of transmission impairments in high baud rate transmission systems

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Abstract *We review our recent work in machine learning and neuromorphic processing for the mitigation of transmission impairments at very high baud rates. Bidirectional recurrent neural networks and neuromorphic recurrent spectral slicers emerge as promising solutions for mid-term deployment in long-haul and short-reach communication systems respectively. © 2022 The Authors*

Introduction

Modern optical communication systems exhibit rapid growth due to the advent of edge-cloud networking architectures that fuel the future of 5G/B5G, edge computing and define how internet will evolve in the next decades. The edge-cloud interconnects require high speed and low consumption optical transceivers for Data Center Interconnects (DCI) and mobile fronthauling. This demand is reflected to industry's incentive to promptly standardise and launch 800G-1.6T to the market [1]. This trend also affects the requirements in metro and long-haul transmission systems where the main objective is to fully exploit installed fibre capacity. In both short-reach and long-haul ecosystems, the goal of ultra-high capacity must be served without substantial increase of power consumption, as telecom carbon footprint is continuously growing during the last ten years and green technologies are indispensable in order to augment capacity in a sustainable way. The main obstacle towards capacity upgrade in both ecosystems is the transmission impairments and the complexity of signal processing required to mitigate them at the digital domain. In long-haul transmission systems, where digital coherent solutions prevail, the main target which is to enhance spectral efficiency is hindered dominantly by nonlinear impairments attributed to Kerr effect [2]. In short-reach transmission systems the principal degradation originates from power fading caused by chromatic dispersion (CD) in intensity modulation/direct detection systems and bandwidth limitations and nonlinearities of transceivers at ultra- high baud rates (> 100 Gbaud) [3].

Although, the two ecosystems have different needs, the advent of cognitive processing either in the digital or in the analog domain seems to be a promising proposition for the sustainable improvement of performance in terms of baud rate and overall capacity. Machine learning and neuromorphic processing are the two sides of the same coin. Machine learning exploits state of the art hardware in order to apply neuro-inspired algorithms for the efficient solution of difficult nonlinear problems. Neuromorphic photonic processing is the on-chip implementation of computing systems that mimic neuro-biological architectures, thus offering elegant solutions in specific problems with almost zero consumption and at latency capped by the speed of light. In the next section, we will first present the special needs of long-haul transmission systems and how they can be served by machine learning models in the form of bi-directional recurrent neural networks (bi-RNNs). Then, we will switch to short-reach transmission systems and show how a neuromorphic recurrent processor can better serve the goal of mitigation of critical transmission impairments at minimum power consumption. In the conclusion we discuss how these two processing propositions may be combined in order to improve transmission performance at reasonable complexity.

Bi- RNNs and the long-haul landscape

Long-haul transmission systems are challenged by the endless upgrade of metro and access networks fueled by bandwidth hungry applications of 5G and Industry 4.0. The capacity crunch in the long-haul will be avoided by either adopting spatial division multiplexing [4] or extension to new bands such as O-, E- and S-bands [5]. In all foreseen roadmaps the capacity requires high order modulation formats (16-QAM and beyond) at high baud rates (>64 Gbaud) and the adoption of superchannels in wavelength division multiplexing scenarios, characterised by ultra-dense arrangement. At the end of the day, the major constraint will be the stimulation of nonlinearities due to Kerr effect and their interaction with amplified spontaneous emission noise which emerge in the form of cross-phase modulation and four-wave mixing between the closely positioned wavelengths and sub-carriers [2]. Many techniques for the compensation of nonlinearities have been proposed in the past such as optical phase conjugation [6], digital back propagation [7], nonlinear Fourier transform [8] and inverse-Volterra series-transfer function [9].

Lately, there exists an increasing interest in the investigation of machine learning techniques for the mitigation of transmission impairments [10]. In 2020, we proposed for the first time the utilization of a bi-directional Long Short-Term Memory (LSTM) network as a post-processing subsystem, which is a well-known efficient RNN model for the compensation of fibre nonlinearities in digital coherent systems for multi-channel polarization multiplexed 16-QAM systems [11]. The specific neural network is very well adapted to fibre channel as its bi-directional configuration copes with its nonlinear dispersive effects. A detailed analysis regarding the consequence of LSTM model parameters and channel memory was conducted in order to reveal the properties of LSTM based receiver with respect to performance and complexity in comparison to Digital Back Propagation (DBP), proving its mitigation superiority in inter-channel transmission effects. In [12] we provided a comparative analysis of the three RNN models, namely LSTM, GRU and Vanilla RNN in WDM systems with small channel spacing and high-order modulation formats. Moreover, we compared the bi-RNN models with a 3rd order Volterra nonlinear equalizer, as a reference technique with the ability to treat complex time-dispersive nonlinear effects, both in terms of performance and complexity. We clearly showed that with the use of many-to-many training, we drastically reduced the complexity of RNN models vs. Volterra whilst keeping their performance superiority in terms of the bit-error rate (BER) of the decoded signal, thanks to bi-RNN ability to track inter-channel inter-dependencies (see fig. 1). We proved that bi-RNN can be almost 90% less complex than a 3rd order Volterra nonlinear equalizer when many-to-many training strategy is chosen. The BER improvement, in conjunction with the vastly improved complexity, constitutes bi-RNN as very promising solutions for the mitigation of prevailing nonlinear effects in long-haul, high-capacity transmission systems at high baud-rates.

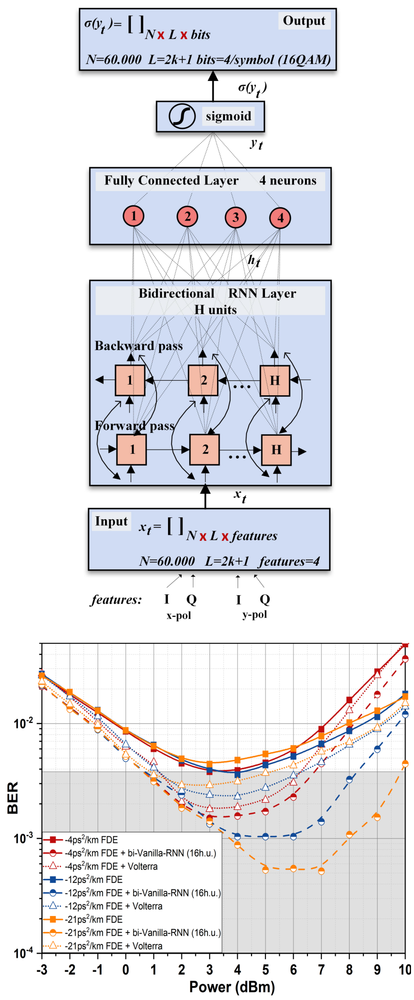

Fig. 1. Bi -RNN (up) Bidirectional-RNN model architecture in the case of 16-QAM (down) BER as a function of optical launched optical power for dispersion of -4, -12 and -21 ps^2/km, with linear equalization, with a bi-RNN of 16 hidden units and Volterra.

Neuromorphic computing and the short-reach landscape

Digital coherent technology is a very attractive candidate for next generation 1.6T links for short reach transmission (< 80 km) at high baud rates as well, however it is still complex and characterized by higher consumption and latency, attributed to the fairly heavy digital signal processing (DSP) [2]. Thus, IM-DD or self-coherent solutions are the prevailing choices for short-reach deployments. Bi-RNN techniques have been proved efficient even for IM-DD systems [13], however their complexity is higher than that of feed forward equalizers (FFE) and increases significantly with the baud rate. The main limitation for direct detection systems is CD induced power fading that is not easy to handle at very high baud rates (>100 Gbaud). Many works in the literature have been devoted to the mitigation of this distortion and a number of techniques such

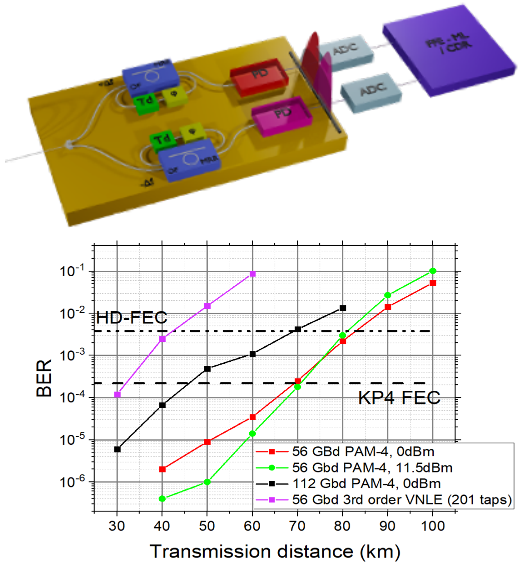

Fig. 2. (up) The architecture of ROSS-NN as a hardware neuromorphic processor for high-speed optical communications signals suffering from CD, bandwidth limitations of the transceiver and nonlinear effects. With the use of a feed-forward equalizer of fairly low complexity, significant restoration of signal fidelity is achieved according to thorough numerical simulations. (down) BER performance as a function of transmission distance in the C-band – 112 Gbaud PAM-4 with recurrent optical filters outperform 56 Gbaud PAM-4 using VNLE.

as Single Sideband (SSB) modulation, digital equalization in the form of DFE [14,15] or Maximum Likelihood Sequence Detectors (MLSD) [16, 17] have been reported. The quadratic dependence of CD on baudrate is the reason why next-generation 112 Gbaud IM/DD links are forced to rely on heavy DSP algorithms that cancel out accumulated dispersion up to 10 km, while for longer links, coherent detection is the only viable, but expensive, solution. Self-coherent techniques in the form of Kramers-Kronig (KK) receiver are an elegant proposition [18] which however is not easily scalable to very high baud rates (>100 Gbaud) [19].

Neuromorphic computing has been lately considered as an option to assist short-reach transmission systems in combatting transmission impairments, mainly CD effects, in an economically viable manner. Very recently, in this context we proposed a photonic integrated neuromorphic enhanced receiver which is also capable of supporting self-coherent detection, thus constituting a modulation format agnostic solution [20]. The receiver relies on recurrent optical spectral slicing neural networks (ROSS-NN) by means of recurrent filter nodes, as proposed in [21], in order to discriminate and separately process different frequency components, thus expanding the dimensionality of the signal processing problem in the optical frequency domain. The proposed receiver can retrieve PAM or QAM formats, alleviating the need of a rather complex KK receiver [18].

ROSS-NN consisting of two nodes is capable of mitigating transmission impairments in an IM/DD system at unprecedented baudrates (> 112 Gbaud) achieving even 60 km reach with very high CD tolerance [19]. The recurrent connectivity offers rich and frequency-dependent memory which is important when transmission impairments are caused by nonlinear channels with memory, such as single-mode fibres. The proposed ROSS-NN, consisting of two recurrent nodes (fig. 1), is successful in mitigation CD because it provides frequency diversity of power fading, characterizing the distorted signals at the two outputs due to CD. This is achieved by treating differently the lower and higher frequency components through spectral slicing of each sideband and by leveraging optical feedback as an extra mechanism to enhance specific frequency components and fading memory. Both outputs are followed by photodiodes with bandwidth lower than the baud rate (<40%) and ADCs that require only one sample per symbol, thus showing that real-life implementation of the scheme is practical at high baud rates (>100 Gbaud) with 40 GHz optoelectronic systems which substantially reduce its cost. Compared to a coherent receiver which requires at least 1.25 samples/symbol in order to decode the signal [22] and 75 GHz optoelectronic components at 120 Gbaud, ROSS-NN receiver is more attractive in terms of cost and complexity taking into account that it requires only a FFE as a back-end DSP unit.

Conclusions

This paper proposes two elegant approaches that leverage machine learning and neuromorphic photonics in order to mitigate transmission impairments in long-haul and short-reach transmission systems. The first approach combats severe inter-channel nonlinear effects in digital coherent systems at low complexity compared to state of the art equalizers. The second approach efficiently mitigates CD at high baud rate short-reach transmission systems. Both solutions could be combined constructively in metro network configurations where a photonic neuromorhic front-end will play the role of a hardware accelerator followed by a lightweight DSP back-end solution relying on bi-RNNs of limited number of hidden units.

Acknowledgements

This project has been partially funded by the EU H2020 NEoteRIC project (871330). K. Sozos and S. Deligiannidis have been supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "2nd Call for H.F.R.I. Research Projects to support Faculty Members & Researchers" (Project Number: 2901)

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