

Title	High dynamic range 100 Gbit/s PAM4 PON with SOA preamplifier using Gated Recurrent Neural Network equaliser
Authors	Murphy, Stephen;Jamali, Fariba;Townsend, Paul D.;Antony, Cleitus
Publication date	2022
Original Citation	Murphy, S., Jamali, F., Townsend, P. D. and Antony, C. (2022) 'High dynamic range 100 Gbit/s PAM4 PON with SOA preamplifier using Gated Recurrent Neural Network equaliser', in Leuthold, J., Harder, C., Offrein, B. and Limberger, H. (eds.) European Conference on Optical Communication (ECOC) 2022, Technical Digest Series (Optica Publishing Group, 2022), paper Th1C.6.
Type of publication	Conference item
Link to publisher's version	https://www.ecoc2022.org/
Rights	© 2022, the Authors. Published by IEEE. ECOC 2022 © Optica Publishing Group 2022.
Download date	2025-07-05 18:18:53
Item downloaded from	https://hdl.handle.net/10468/13892

High Dynamic Range 100 Gbit/s PAM4 PON with SOA Preamplifier using Gated Recurrent Neural Network Equaliser

Stephen Murphy⁽¹⁾, Fariba Jamali⁽¹⁾, Paul D. Townsend⁽¹⁾, Cleitus Antony⁽¹⁾

⁽¹⁾ Photonics Systems Group, Tyndall National Institute, Dyke Parade, Cork, Ireland, T12 R5CP

*Email: stephen.murphy@tyndall.ie

Abstract We investigate parallel multi-symbol equalisation scheme for 100Gb/s/λ PAM4 using Gated Recurrent Neural Networks and exploit SOA preamplifier gain suppression to achieve 27 dB system dynamic range below hard-decision FEC BER limit of 3.8×10^{-3} using a receiver with two gain settings. © 2022 The Author(s)

Introduction

Recently published ITU-T Higher Speed Passive Optical Network (PON) standards outline the requirements for next generation 50G PON aimed at meeting ever-increasing demand for high-speed Fiber-to-the-Premises [1]. Future PON standards targeting single channel 100 Gb/s and beyond operation may need to transition to new solutions based on either coherent modulation and reception techniques or Intensity Modulation with Direct Detection (IM/DD) with the addition of optical amplification to meet the challenging minimum optical loss budget for PON of 29 dB [1]. In this paper, we present a potential IM/DD solution based on 50 Gbaud, 4-level Pulse Amplitude Modulation (PAM4) for 100Gb/s operation. Compared to non-return-to-zero (NRZ) modulation, PAM-4 is an attractive solution due to its reduced electro-optic bandwidth requirements, albeit at the cost of reduced receiver sensitivity. However, the latter can be compensated by using Semiconductor Optical Amplifiers (SOAs) as receiver pre-amplifiers. SOAs are attractive solutions as they are readily integrable, can operate in the C- and O-bands, and are relatively low-cost.

However, the impact of SOA non-linearities such as gain saturation-induced patterning effects is a concern, especially in the upstream direction in PONs. This is due to the high Dynamic Range (DR), burst mode nature of the signalling, with the new 50G PON standards specifying values as high as 19.5 dB DR for loud-soft burst ratio [1]. It has been shown that PAM4 signalling is highly sensitive to SOA gain saturation-induced patterning effects [2], which makes it difficult to avoid large power penalties for the high power, loud bursts. However, Machine Learning (ML) based equalisation techniques such as Recurrent Neural Networks (RNNs) have been shown to be capable of compensating these impairments, among others [3, 4]. This suggests an intriguing further possibility; if such an equaliser can enable the

SOA to operate in gain saturation with tolerable patterning impairments, can the associated SOA gain suppression be exploited to reduce the input optical DR to the following photo-receiver? This could be particularly advantageous given the challenges of designing 50 Gbaud-, high dynamic range-capable burst mode receivers (BMRx) with sufficient linearity to support PAM-4 modulation. Such a BMRx for 25Gbaud operation is discussed in [5]. Furthermore, can the ML equaliser also compensate for electronic non-linearities in the adjustable gain trans-impedance amplifier (TIA) of the BMRx?

In this work we demonstrate a 100 Gbit/s PAM4 system that achieves 30 dB optical loss budget, and up to 28 dB back-to-back (B2B) DR using a fixed bias SOA optical preamplifier followed by an Rx with two gain settings. The SOA gain suppression is exploited by using the GRU-based RNN equalisation scheme proposed by us in [6]. However, as others have noted, there exists difficulties in implementing neural network equalisers in hardware [7], and so we extend our analysis of the RNN equaliser to include parallel multi-symbol output schemes as seen in [4, 8, 9]. These are advantageous for future real-time FPGA or ASIC hardware implementations due to reduced multiply-accumulate operations per equalised symbol, and GRU feedback rate

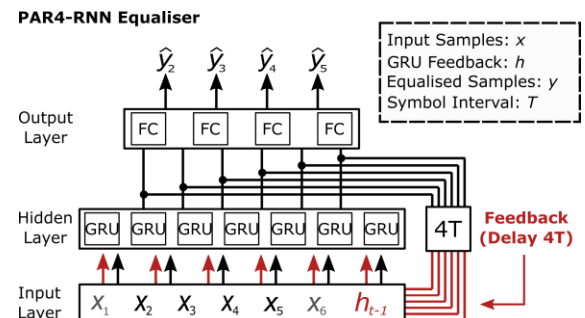


Fig. 1: PAR4-RNN equaliser predicts four consecutive symbols simultaneously. Feedback is only required once every four symbols thus relaxing DSP timing requirements.

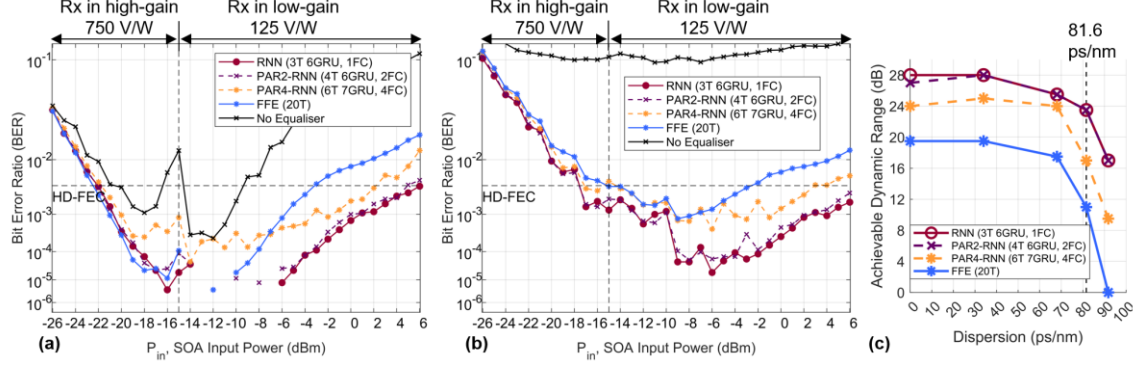


Fig. 3: BER performance for various equalisers in (a) back-to-back and (b) transmission over a fibre length with 81.6ps/nm dispersion. Achievable dynamic range for various dispersion values shown in (c).

adaptation in a PON Rx, and the gain is changed from low to high setting at -14 dBm input to the SOA / OLT as shown in Fig. 2 (c). The photoreceiver electrical output is also shown, representing the amplitude swing between the PAM4 outer symbols. The Rx has linear response ($< 3\%$ THD - Total Harmonic Distortion) up to a differential output swing of 450 mV, and the eye diagrams in Fig. 2 (d) show clear degradation due to Rx non-linearities and SOA patterning.

Waveforms are captured using a 100 GSa/s real time scope with 33 GHz bandwidth, while a 4th-order Bessel filter is applied digitally to imitate 25G class opto-electronics. Offline processing is then carried out, before DSP using 1 sample per symbol is applied and final error analysis occurs.

Results

Fig. 3 (a) shows the 100 Gb/s PAM4 system back-to-back (B2B) performance for PAR2- and PAR4-RNN equalisers, as well as single output RNN and 20-tap (20T) FFE for comparison. The optically preamplified Rx sensitivity is measured to be -22 dBm at the hard-decision forward error correction (HD-FEC) threshold BER of 3.8×10^{-3} . Assuming $+8$ dBm launch power, this corresponds to an optical power budget of 30 dB. Rx non-linearities result in the distinctive “W” performance curve seen in Fig. 3 (a) for the no equaliser case, meaning DSP is required to enable two gain settings operation at the Rx. The PAR2- and PAR4-RNN equalisers overcome the combination of bandwidth limitation, SOA patterning, and Rx non-linearities to achieve 27 dB and 24 dB optical DR respectively. This approaches the RNN equaliser performance of

28 dB DR, while preserving similar equaliser structure and reduced complexity, as detailed in Table 1.

Fig. 3 (b) shows equaliser performance over total system DR for fibre transmission totalling 81.6 ps/nm in the C-band. The RNN equalisers achieve below HD-FEC threshold BER up to $+6$ dBm input to the OLT, and consistently achieve higher DR than FFE over a wide range of dispersion values as seen in Fig. 3 (c).

Table 1 compares equaliser complexities in terms of trained parameters and multiply-accumulate operations per symbol, where the parallel RNNs show competitive performance. By going from single-symbol output RNN equaliser to PAR4-RNN which predicts simultaneously 4 consecutive symbols, the number of parameters increases by only a factor of 1.75, and the multiply-accumulate operations per equalised symbol decreases by 55%.

Conclusions

In summary, we demonstrate a 100 Gb/s PAM4 system with 28 dB dynamic range by exploiting SOA preamplifier gain suppression and using two gain setting scheme at the Rx. Equalisation based on Gated Recurrent Units is shown to overcome associated SOA patterning and Rx non-linearities, and we further demonstrate computational advantage of PAR-RNN equalizers.

Acknowledgements

This work is supported by Science Foundation Ireland (SFI) grant 12/RC/2276P2.

Table 1: Comparison of neural network equaliser performance, parameters and associated multiply-accumulate operations.

Equaliser	Input Taps	Structure	Parallel Outputs	Parameters	Multiply-Accumulate Operations per Symbol	SOA Input Power Dynamic Range		
						0ps/nm	81.6ps/nm	91.8ps/nm
RNN	3T	(6GRU, 1FC)	1	187	168	28dB	23.5dB	17dB
PAR2-RNN	4T	(6GRU, 2FC)	2	212	96	27dB	23.5dB	17dB
PAR4-RNN	6T	(7GRU, 4FC)	4	326	75.25	24dB	17dB	9.5dB

References

- [1] Recommendation ITU-T G.9804.3, "50-Gigabit-capable passive optical networks (50G-PON): Physical media dependent (PMD) layer specification," <http://handle.itu.int/11.1002/1000/14714>, September 2021.
- [2] Li Z, Li Y, Luo S, Yin F, Wang Y, Song Y, "SOA Amplified 100 Gb/s/λ PAM-4 TDM-PON Supporting PR-30 Power Budget with >18 dB Dynamic Range," *Micromachines* (Basel), 2022 Feb 22;13(3):342. doi: 10.3390/mi13030342.
- [3] K. Wang, C. Wang, J. Zhang, Y. Chen and J. Yu, "Mitigation of SOA-Induced Nonlinearity With the Aid of Deep Learning Neural Networks," in *Journal of Lightwave Technology*, vol. 40, no. 4, pp. 979-986, 15 Feb.15, 2022, doi: 10.1109/JLT.2021.3126765.
- [4] B. Sang et al., "Multi-Symbol Output Long Short-Term Memory Neural Network Equalizer For 200+ Gbps IM/DD System," 2021 European Conference on Optical Communication (ECOC), 2021, pp. 1-4, doi: 10.1109/ECOC52684.2021.9606010.
- [5] X. Yin, G. Coudyzer, P. Ossieur, L. Breyne, B. Van Lombergen and J. Bauwelinck, "Linear Burst-Mode Receivers for DSP-Enabled Passive Optical Networks," 2021 Optical Fiber Communications Conference and Exhibition (OFC), 2021, pp. 1-3.
- [6] S. Murphy , Paul D. Townsend, Cleitus Antony, "Recurrent Neural Network Equalizer to Extend Input Power Dynamic Range of SOA in 100Gb/s/λ PON", to appear in 2022 Conference on Lasers and Electro-Optics (CLEO), 2022.
- [7] X. Huang, D. Zhang, X. Hu, C. Ye and K. Zhang, "Low-Complexity Recurrent Neural Network Based Equalizer With Embedded Parallelization for 100-Gbit/s/λ PON," in *Journal of Lightwave Technology*, vol. 40, no. 5, pp. 1353-1359, 1 March1, 2022, doi: 10.1109/JLT.2021.3128579.
- [8] N. Kaneda, Z. Zhu, C. Chuang, A. Mahadevan, B. Farah, K. Bergman, D. Van Veen, and V. Houtsma, "FPGA Implementation of Deep Neural Network Based Equalizers for High-Speed PON," in *Optical Fiber Communication Conference (OFC) 2020, OSA Technical Digest (Optica Publishing Group, 2020)*, paper T4D.2.
- [9] N. Kaneda, C. Chuang, Z. Zhu, A. Mahadevan, B. Farah, K. Bergman, D. Van Veen, V. Houtsma, "Fixed-Point Analysis and FPGA Implementation of Deep Neural Network Based Equalizers for High-Speed PON," in *Journal of Lightwave Technology*, vol. 40, no. 7, pp. 1972-1980, 1 April1, 2022, doi: 10.1109/JLT.2021.3133723.
- [10] Cho, K., "Learning Phrase Representations using RNN Encoder-Decoder for Statistical Machine Translation", arXiv e-prints, 2014, doi: 10.48550/ARXIV.1406.1078.
- [11] P. J. Werbos, "Backpropagation through time: what it does and how to do it," in *Proceedings of the IEEE*, vol. 78, no. 10, pp. 1550-1560, Oct. 1990, doi: 10.1109/5.58337.