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Authors	Dalla Santa, Marco;Antony, Cleitus;Talli, Giuseppe;Townsend, Paul D.
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25Gb/s PAM4 Adaptive Receiver Equalisation Requirements for Burst-Mode Transmission Systems

Marco Dalla Santa[(1)], Cleitus Antony[(1)], Giuseppe Talli[(1)], Paul D. Townsend[(1)]

[(1)] Tyndall National Institute, University College Cork, Cork, Ireland marco.dallasanta@tyndall.ie

Abstract *Requirements for burst-mode equalisation in a 25Gb/s PAM4 system for passive optical network upstream traffic are analysed for different linear equaliser solutions, with transmission over 40km of fibre. The impact of chromatic dispersion, transmitter bandwidth restriction and non-linearities is considered.*

Introduction

Growth in broadband services worldwide is driving the demand for higher speed passive optical networks (PONs). To reach higher data-rates in a cost-effective manner, wavelength-division multiplexing has been introduced in the latest NG-PON2 standard to increase the total data-rate to 4x10Gb/s by essentially stacking four XG-PON systems[1]. On the road towards 100Gb/s networks, research activities are now aiming to implement 4x25Gb/s systems which require 25Gb/s single line speed. A potentially cost-effective way to achieve this would be to exploit mature 10G-class optoelectronics by expanding device bit-rates with the aid of higher order modulation formats and digital signal processing (DSP) techniques. Promising modulation solutions for 25Gb/s operation that go beyond standard on-off keying (OOK) non-return to zero (NRZ) are four-level pulse amplitude modulation (PAM4) and optical or electrical duo-binary[1-3]. PAM4 is a strong candidate since it requires half of the bandwidth of OOK for the same bit-rate, having twice the spectral efficiency, and is more resilient to chromatic dispersion. However, the requirement on linearity is more stringent and higher optical power at the receiver is needed compared to NRZ. PAM4 modulation has been proposed for PON downstream where the transmission is continuous. Pre-emphasis techniques can be adopted in the optical line terminal (OLT) transmitter and further post-equalisation is also required at the optical network unit (ONU) receiver. Recent demonstrations of such PAM4 systems for continuous mode PON downstream channels have shown that 10G optical components can be used to achieve bit-rates up to 40Gb/s with various DSP compensation[2,3] and equalisation techniques[4]. PAM4 is also a viable option to increase the upstream bit-rate where the transmission is in burst-mode. In this case, the simplicity, low cost and low power aspects of the ONU transmitter should be maintained and hence complex DSP pre- equalisation should be avoided. Moreover, in upstream every burst is generated by a different transmitter with a certain bandwidth and degree of non-linearity, and experiences a different optical path length with a different degree of chromatic dispersion. The post-equalisation must therefore be able to adapt on a burst-by-burst basis to provide optimum compensation[5]. Real-time operation of DSP-aided 40Gb/s PAM4 with 10G upstream devices working in continuous mode has been reported[6].

In this work, we present a burst-mode analysis of equaliser performance for post-compensation. We aim to simplify the ONU transmitter by eliminating pre-equalisation and using DSP only in the OLT receiver which is shared by all users. In the following we provide an analysis of linear feed-forward or decision-feedback equalisers (FFE or DFE) for a burst-mode 25Gb/s PAM4. The equaliser size, tap spacing and training sequence length requirements are analysed using offline processing for different trunk line lengths and chromatic dispersion, and various transmitter bandwidths and non-linearities. We also explore the possibility of employing FFE integrated circuits designed to operate with NRZ, by analysing the penalty introduced by using a binary training sequence rather than a quaternary PAM4 sequence.

Experimental Setup

The PAM4 electrical driving signal is generated by combining two binary NRZ streams with different amplitudes by means of a power combiner. Custom patterns are designed for burst-mode operation including guard-bands and preambles for burst-mode receiver gain setting and equaliser training. Two different packets are generated whose payload is a pseudo-random quaternary sequence (PRQS) of order 7, inverted in one of the packets. Gray coding is adopted in the PAM4 signal to minimise the bit-error-rate (BER). The ONU transmitter is a C-band tuneable laser followed by an off-the-shelf 10G electro-absorption modulator (EAM). The emitting wavelength is 1539.371nm (194.75THz channel

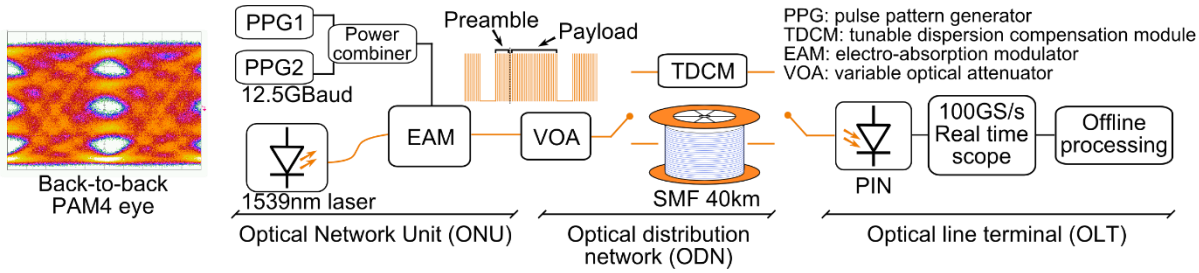


Fig. 1: Experimental setup diagram.

on the 50GHz ITU grid) to conform to the upstream band specification of the NG-PON2 standard[1]. The relative amplitudes of the two NRZ signals can be adjusted to compensate or enhance the non-linear response of the EAM. The optical signal is then sent to a variable optical attenuator (VOA), which controls the optical power entering the standard single-mode fibre (SSMF) of the optical distribution network (ODN), or a tuneable dispersion compensation module (TDCM), which can emulate chromatic dispersion between ±1500ps/nm. At the OLT side, a commercial 10GHz PIN photodiode with a linear transimpedance amplifier (TIA) is used as the receiver. The output waveform of the photodiode is then captured with a 100GS/s real-time oscilloscope and processed offline for equaliser implementation and error performance evaluation. Adaptive burst mode FFE and DFE equalisers are implemented, where the tap values are set during the 1000 symbol packet training sequence for every incoming burst and then used for equalisation of the payload. In every packet the preamble contains a PRQS used for equaliser training, or a pseudo-random binary sequence (PRBS) when the FFE equaliser is trained with a simple NRZ sequence. The NRZ symbols correspond to the outer PAM4 constellation symbols in order to have equal signal amplitudes.

Result discussion

Fig. 2 shows BER performance as a function of optical received power for transmission over a 40km SSMF. The target pre-forward error correction (FEC) BER of 10^{-3} can be achieved in optical back-to-back (B2B) without post-equalisation for a received power of −16.1dBm. A fractionally-spaced (T/2) FFE can achieve 1.4dB gain, with no significant improvement observed with a DFE added. After 40km of SSMF a 10^{-3} BER cannot be achieved without post-equalisation and different sizes of FFE and DFE are compared. The optimum number of FFE taps is equivalent to 13 symbols as larger sizes do not provide additional improvement. For this FFE size, the optimum DFE size is found to be 5 taps which offers a further 0.7dB improvement for 40km transmission. A 2.2dB penalty is observed between a fractionally spaced equaliser (ffe-13 T/2; 26 taps) and symbol spaced equaliser (ffe-13 T; 13 taps) of the same size. Symbol spaced equalisers generally have worse performance than fractionally spaced equalisers as they cannot perform Nyquist filtering and are more sensitive to phase sampling delay, however their implementation is simpler as only symbol-rate sampling is required.

The above equalisers are then analysed for increasing chromatic dispersion introduced with the TDCM. The results are shown in Fig. 3 where the received optical power required for a BER of 10^{-3} is plotted. For total chromatic dispersion values above 400ps/nm the target BER of 10^{-3} cannot be achieved without the aid of equalisation. The graph shows how a DFE offers a considerable advantage over a FFE for >600ps/nm total dispersion, being otherwise comparable. The performance of an FFE trained with an NRZ PRBS signal is also shown for

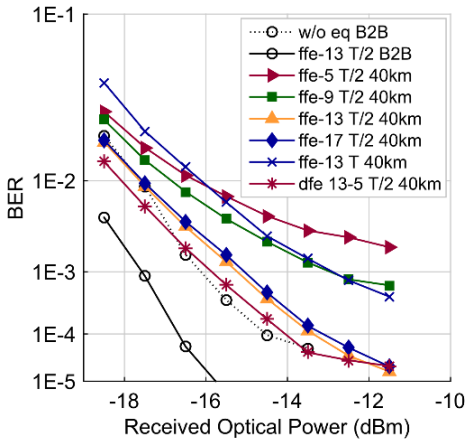


Fig. 2: BER trend for different equalisers after 40km SMF.

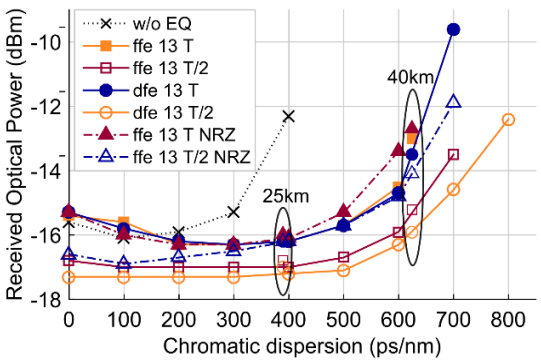


Fig. 3: Chromatic dispersion induced penalty, BER=10^{-3}.

comparison offering a 1dB penalty after 40km SSMF.

Fast adaptation of the equaliser is necessary for operation in a burst-mode network, as burst-by-burst training is required. The mean square error (MSE) of the equalised signal with the fractionally spaced ffe-13, T/2, 26 taps is reported in Fig. 4 for different training sequence lengths up to 1000 symbols. Convergence of the taps to an optimised value is observed within the first 500 training symbols, showing the potential of these equalisation techniques to operate in burst-mode with a small packet overhead. Fig. 4 also shows how the equaliser behaves for a binary or quaternary training sequence for a fixed input power (BER of 10^{-3} with PRQS training). A PRQS training sequence performs better (MSE=2%), but only small increases in MSE of 0.1% in B2B and 0.5% with 40km of fibre are observed with NRZ training, and the convergence rate is similar.

Finally the effect of impairments introduced by the ONU transmitters, such as bandwidth restriction and non-linearities are investigated with the above equalisers (Fig. 5). If the transmitter bandwidth is reduced down to 5GHz signal recovery is possible in B2B with penalties up to 2dB. Over 40km of SSMF all the equalisers can still support transmission with a 7.5GHz bandwidth, but only the fractionally spaced DFE can reach BER of 10^{-3} with a 5GHz transmitter. The effect of modulator non-linearities are quantified by adopting the "level separation mismatch ratio" metric, as suggested for PAM4 in IEEE P802.3bj clause 94. Transmitter non-linearities are induced varying the amplitude of the NRZ signals from the PPG. FFE and DFE can both mitigate this impairment, however due to their linear nature they cannot recover a heavily non-linearly distorted signal.

Conclusions

The performance of different post-equalisers for a 25Gb/s PAM4 burst-mode transmission have been reported. For distances up to 40km, simple FFE and DFE schemes compensate the dispersion and transmitter bandwidth limitations without the need of transmitter pre-emphasis. The equalisers can work in burst-mode requiring less than a 1000 symbol training sequence. Remarkably, a binary training sequence can also be used for FFE training with only a small reduction in performance, opening the possibility of using FFEs developed for NRZ signals.

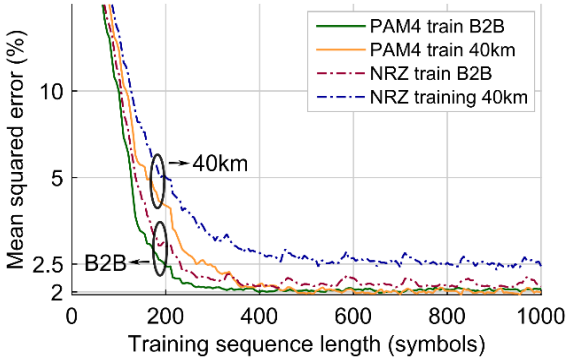


Fig. 4: MSE trend versus training sequence length.

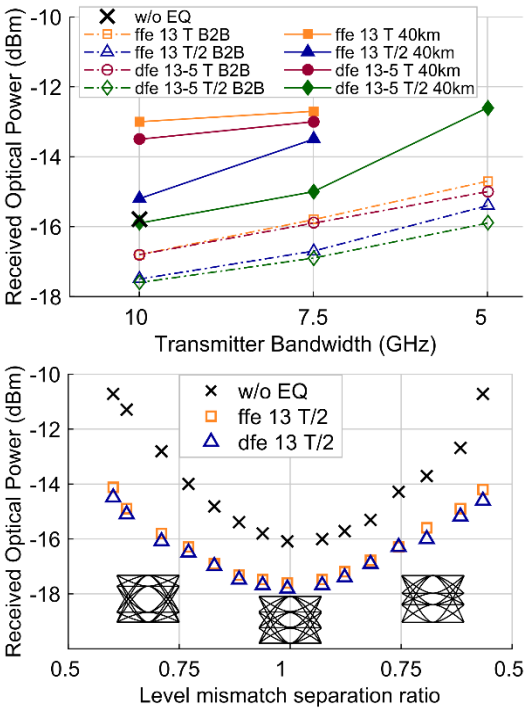


Fig. 5: Transmitter induced impairments, BER=10^{-3}

Acknowledgements

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