Single Lane 168 Gb/s PAM-8 Short Reach Transmission Using an EAM with Receiver Skew Compensation

Colm Browning(1), Marco Ruffini(2), Barry Cardiff(3) and Liam P. Barry(1)

(1) School of Electronic Engineering, Dublin City University, Glasnevin, Dublin 9, Ireland, *colm.browning@dcu.ie*

(2) CONNECT Research Centre, Trinity College Dublin, Dublin 2, Ireland.

(3) School of Electrical & Electronic Engineering, University College Dublin, Belfield, Dublin 4, Ireland

Abstract *Future data centre networks require high single lane data rate optical links. This paper experimentally demonstrates transmission of 56GBd PAM-8, in the C-band, using a low drive voltage electro-absorption modulator. 0.5dB performance improvement is achieved through digital receiver eye-skew compensation.*

Introduction

The continued proliferation of connected devices and ever-increasing popularity of cloud based services means that the enormous strain placed on the networks inside, and between, data-centres (DC) shows no signs of abating.

In response, the IEEE has recently ratified the 803.3bs standard[1] which encapsulates 200 and 400 gigabit Ethernet (GbE). The standard makes use of 4/8 wavelength multiplexed lanes of 50Gb/s four level Pulse Amplitude Modulation (PAM-4) for transmission rates up to 400Gb/s, and over distances up to 2km. The choice of direct modulation in combination with PAM offers relative simplicity of implementation which is highly desirable for DC networks where power and cost efficiency are of critical importance[2].

Looking beyond 400GbE, scaling of 50Gb/s PAM-4 links may become problematic as the bandwidth limitations inherent to direct modulation mean that a prohibitively large number of transmission lanes may be required – leading to increased transceiver footprint, complexity and cost. In order to facilitate future DC scaling, higher per-lane date rates must be implemented. This looks likely to be achieved through the use of high speed, higher order advanced modulation – the bandwidth requirements of which will be facilitated by a shift toward *external modulation*[3].

For PAM-4 based interconnects, a record data rate of 214Gb/s was reported by Kanazawa et al.[3] using a 59GHz modulation bandwidth electro-absorption modulator (EAM) with integrated Distributed Feedback (DFB) laser. Compared to widely deployed Mach-Zehnder Modulators (MZM), EAMs typically exhibit high modulation bandwidth and are more compact. The EAM's relatively high level of imparted frequency chirp is far less problematic for short reach applications and crucially, for DC networks, they typically require a low RF drive voltage ~1V, leading to increased power efficiency.

It follows that recent demonstrations have focussed on maximising throughput and spectral efficiency with these modulators. 112Gb/s PAM-4 transmission using an EAM with 50GHz modulation bandwidth has recently been reported[4]. Increased spectral efficiency through the use of PAM-8 at 32Gbd[5] and 40Gbd[6] have also been demonstrated with an EAM for transmission distances of 4 and 2km respectively. 56Gbd (168Gb/s) PAM-8 short reach transmission has been reported in [7], however this demonstration employed an MZM at the transmitter.

In this work, we report the successful transmission of 168Gb/s PAM-8 using a 40GHz EAM, over 2km of standard single mode fibre (SSMF). To best of the authors' knowledge, this is the highest data rate PAM-8 demonstration using an EAM. Additionally, PAM eye de-skewing is implemented at the receiver, resulting in a 0.5dB improvement in receiver sensitivity.

Receiver Eye-Skew Compensation

The external modulation of a laser source using an EAM can lead to timing-skew of a high symbol rate PAM eye-diagram. This effect causes an *amplitude dependent time delay* across the multi-level PAM symbols to be transmitted, and has been highlighted in[8] which shows this impairment for 4 and 8 level PAM signals. Indeed, the experimentally measured eye diagrams presented[3,6] both appear to exhibit some amount of skew across the PAM-4 and PAM-8 levels respectively. Digital de-skewing at the receiver side has previously been employed for duo-binary PAM-4 short reach applications using an EAM[8], but not for PAM-8.

Consider a series of n sampled PAM symbols $x_n \triangleq x(nT)$ where T is the symbol period. The approach taken in this work was to substitute the n^{th} signal sample by an estimate of the signal at some small time step, τ_n, earlier i.e. each x_n is replaced by $x'_n \triangleq x(nT - \tau_n)$, and τ_n is a function of the amplitude of the received sample, $|x_n|$. Practically, x'_n can be obtained using a truncated Taylor series:

$$x(nT - \tau_n) \cong x_n - \tau_n \frac{d}{dt} x_n(T) \triangleq x'_n$$

The derivative in the above equation can be estimated using a linear phase Finite Impulse Response (FIR) based filter leading to the structure shown in Fig. 1 which is implemented in the system receiver.

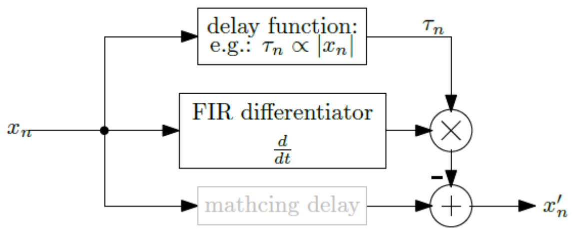

Fig. 2: Skew compensation structure.

This approach differs to those taken in[8] in that a Look Up Table (LUT) is not required as the amount of de-skewing applied is calculated using a formula which is based on the instantaneous value of the received signal. The proposed compensator requires some level of oversampling to perform interpolation using the 11-tap FIR filter, and 5 samples per symbol were used in this case.

Experimental Setup

The experimental test-bed is shown in detail in Fig. 2. PAM-8 sequences, at 56Gbd, were generated offline in Matlab, digitally up-sampled and loaded into a Keysight Arbitrary Waveform Generator (AWG) operating at 86 GSa/s. The output signal amplitude was set at $850mV_{pk\text{-}pk}$ and this was used to directly drive the EAM which was biased via a DC bias tee. No additional electrical amplification was required.

A commercial EAM, exhibiting a modulation bandwidth of 40GHz and insertion loss of 10dB at 1550nm, was used to modulate the +10dBm output of a tuneable laser (TL). The modulated light signal was transmitted over 2km of SSMF at a launch power of 0dBm before being amplified at the receiver by an Erbium Doped Fibre Amplifier (EDFA) - which was required to overcome losses (fibre, connectors, filter and EAM). An Optical Band-Pass Filter (OBPF) was used to suppress Amplified Spontaneous Emission (ASE). A 10% portion of the signal was tapped in order to observe frequency domain information on an Optical Spectrum Analyser (OSA). The remainder of the signal was passed through a Variable Optical Attenuator (VOA) which was used to control the power of the light falling on the receiver PD which was a 50GHz u^2t PIN diode. The electrical signal was then sampled by a Tektronix Real Time Oscilloscope (RTS) operating at 200GSa/s.

Down-sampling, de-skewing, timing synchronisation, Equalisation (EQ) and Bit Error Rate (BER) measurement were performed digitally offline. The adaptive EQ used was a 61 tap FIR filter, with tap weights updated using a Decision-Directed Least-Mean Square (DD-LMS) algorithm. The symbol synchronization was performed with the aid of a training sequence which consisted of 32 PAM-8 symbols.

Results and Discussion

Fig. 3 shows PAM-8 eye diagrams successfully received at 192.8THz in the system outlined. Fig. 3(a) exhibits skew as the higher amplitude PAM eyes lag the central ones (BER = 3.42×10^{-3}), while Fig. 3(b) shows the successfully de-skewed eye diagram for the same conditions with improved performance (BER = 2.6×10^{-3}).

EAMs exhibit wavelength dependent characteristics such as insertion loss, chirp and modulation extinction ratio/transmission profile. Transmission was tested when the tuneable laser was tuned to four separate operating frequencies: 192.0, 192.8, 193.4 and 193.8THz.

Fig. 4 shows received optical power versus BER for all C-band test frequencies when skew compensation is applied, and example cases where the compensation is de-activated. The figure shows successful transmission of the 168Gb/s signal at 192.8THz (1554.94nm) with and without skew compensation. For a received power of +7dBm, BER is calculated (below the 7% Forward Error Correction (FEC) limit of 3.8×10^{-3}) as 2.6×10^{-3} with compensation and 3.42×10^{-3} without. Comparing BER at this

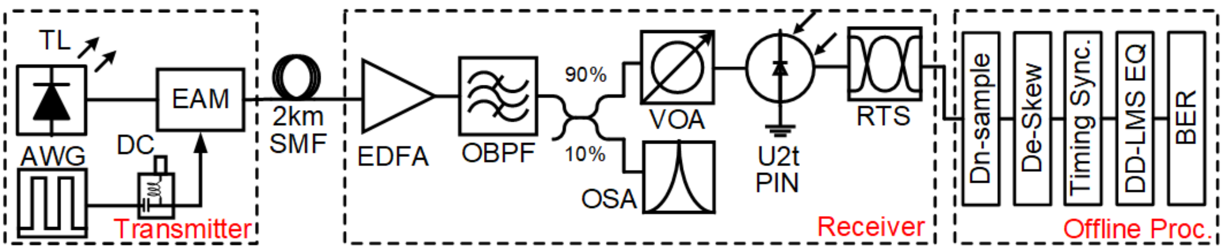

Fig. 2: 56Gbd PAM-8 transmission experimental test-bed.

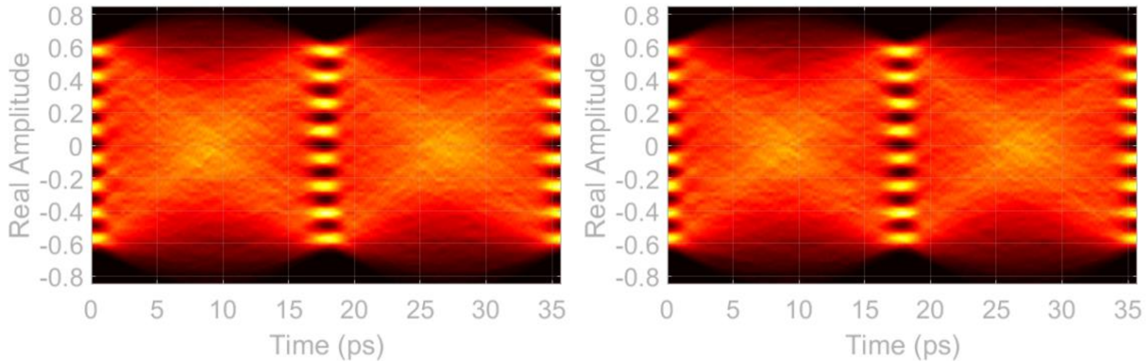

Fig. 3: 56Gbd PAM-8 eye diagrams exhibiting skew (a) and with receiver skew compensation (b).

frequency at the FEC threshold, the figure shows a 0.5dB gain in receiver sensitivity when is de-skewing implemented.

The figure also shows slightly degraded performance for the 192.0THz (1561.49nm) channel where a BER (just above the FEC threshold) of 3.82×10^{-3} is observed in the case where no compensation is applied, and at a received power of +7dBm. Applying the digital de-skewing lowers the BER below the threshold to 3.2×10^{-3} making PAM-8 transmission with this EAM feasible at this frequency.

Changes in EAM modulation efficiency induced by changing to operating frequencies of 193.4 and 193.8THz resulted in reduced performance due to degraded signal-to-noise (SNR) of the received signals. This highlights how, for DC networks which will scale through higher bandwidth external modulation, the choice of EAMs which allow greater wavelength interoperability will be a key factor.

Conclusions

Scaling future DC networks will require higher single-lane transmission rates as expansion through increased channel count will lead to greater footprint and complexity. EAMs are a promising solution as they provide high modulation bandwidth and efficiency through low drive voltages. Results in this paper have demonstrated how 168Gb/s PAM-8 short reach transmission can be achieved with a 40GHz EAM. A 0.5dB performance improvement is achieved through novel receiver de-skewing – with potential for further impact on increased PAM-4/8 transmission ≥100Gbd, helping to facilitate DC network scaling beyond 400GbE.

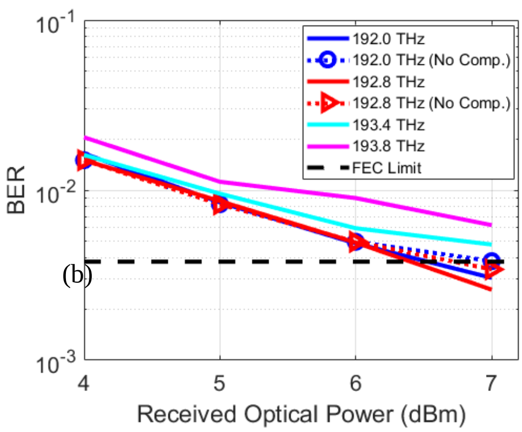

Fig. 4: Received power versus BER for skew (un)compensated 56 Gbd PAM-8 at various frequencies.

Acknowledgements

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