Single-Lane >100 Gb/s CAP-based Data Transmission over VCSEL-MMF Links using Low-Complexity Equalization

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ABSTRACT

In this paper, we review recent work on the development of a novel low-complexity equalizer that can enable single-lane >100 Gb/s short-reach optical links based on carrierless amplitude and phase modulation. This equalizer, named the CAP equalizer, can mitigate the transmission impairments in the link due to a non-ideal channel frequency response, providing significant performance advantage over conventional FFE and DFE equalizers and enabling higher data rates and longer reach. Its use is demonstrated in a VCSEL-based MMF link achieving data transmission of 112 and 124 Gb/s over 100 m OM4 MMF.

Keywords: carrierless amplitude and phase modulation, equalization, short-reach optical links, multimode fibre links, vertical-cavity surface emitting lasers, optical interconnects, feedforward equalizers, decision feedback equalizers

1. INTRODUCTION

The ever increasing demand for communication bandwidth within data centres, data storage systems and supercomputers is pushing the need for high-capacity yet low-cost short-reach optical links. Currently, 400 and 800 Gb/s optical links are under development. Their implementation relies on the deployment of high-speed parallel lanes. For example, 400 Gb/s can be achieved with 4×100 Gb/s links or 8×50 Gb/s or 16×25 Gb/s [1]. The use of lower number of lanes can provide important cost, power efficiency and footprint advantages. As a result, the development of single-lane >100 Gb/s short-reach optical links is highly desirable. However, achieving such data rates with low-cost optical components is not straightforward due to their bandwidth limitation. As a result, spectrally-efficient modulation formats and equalization have attracted considerable interest in recent years as they can overcome this bandwidth limitation [2-5]. Carrierless phase and amplitude modulation is one such scheme that offers high spectral efficiency and ease of implementation [4, 6, 7]. Its main advantages over other commonly-employed modulation formats can be summarised in the following: (i) it removes baseline wander issues which are common in pulse amplitude modulation (PAM) schemes, (ii) it does not require the use of mixers and local oscillators which are essential in quadrature amplitude modulation (QAM), (iii) it allows flexible implementation as it can be applied with either analog or digital electronics and, (iv) contrary to orthogonal frequency division multiplexing (OFDM) schemes, it does not require digital signal processing, and offers lower peak-to-average power ratio (PAPR). The use of CAP modulation has been demonstrated in different types of optical links enabling higher data rates beyond what can be achieved with conventional non-return-to-zero (NRZ) modulation [4, 7-10]. However, its performance can be severely impacted when the link frequency response is non-ideal, resulting in intersymbol (ISI) and channel crosstalk interference (CCI) [8]. We have recently developed a novel equalizer type, named the CAP equalizer, which can be realised with small additional complexity from conventional feedforward (FFE) and decision feedback (DFE) equalizers and which can efficiently mitigate these transmission impairments enabling higher data rates and longer reach [8, 11]. This novel equalizer can be implemented both at the transmitter and received side providing flexibility in the system design. Here, we review its structure and operation and report the data transmission of 112 and 124 Gb/s CAP-16 over a VCSEL-based 100 m OM4 MMF link. The conventional FFE and DFE equalizer of the same length fails at these data rates and MMF reach. The use of the CAP equalizer at the transmitter side results in a receiver sensitivity of -3.5 and -1.2 dBm at 112 and 124 Gb/s respectively which is a significant improvement of ~1.8 dB over the respective CAP post-equalizer.

2. CAP MODULATION AND CAP EQUALIZER STRUCTURE

Carrierless amplitude and phase (CAP) modulation is a spectral-efficient modulation scheme that relies on the transmission of two orthogonal passband channels, conventionally named the in-phase (I-) and quadrature (Q-) channel. Figure 3 shows a high-level schematic of a typical CAP-based transmission scheme. The data is encoded on each channel according to the employed encoding scheme, and the two channels are then combined and transmitted over the channel. At the receiver, the two channels are separated using matched filters and the decision on the transmitted symbols is performed. However, the orthogonality of the two channels is destroyed when the amplitude of the link response is not flat and/or the phase response non-linear [8]. These result in ISI and CCI between the two channels which degrade the link performance. As a result, equalization is employed to mitigate the ISI in the link and enable the successful recovery of the transmitted symbols at the receiver. Different types of linear and non-linear equalizers can be used [12-15], with one of the simplest type being a combination of feedforward (FFE) and decision feedback (DFE) equalizers. These rely on finite impulse response filters that comprise fixed delay lines and tuneable tap coefficients (Figure 2) and can be easily implemented. The FFE part can be applied either at the transmitter side of the link as a pre-equalizer or at the receiver side as a post-equalizer. The latter enables easier implementation as the equalizer tap coefficients can be readily adapted at the receiver using equalizer training based on the transmission of a known data sequence and equalizer training, but results in additional power penalty due to noise enhancement. The former on the other hand, provides better noise performance as there is no noise enhancement involved, but requires bi-directional communication and information exchange between the receiver and transmitter for the optimisation of the equalizer tap coefficients.

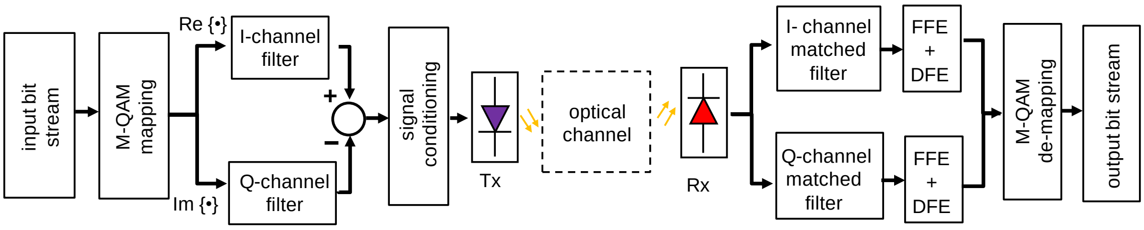


Figure 1. Diagram of a typical CAP-based transmission scheme.

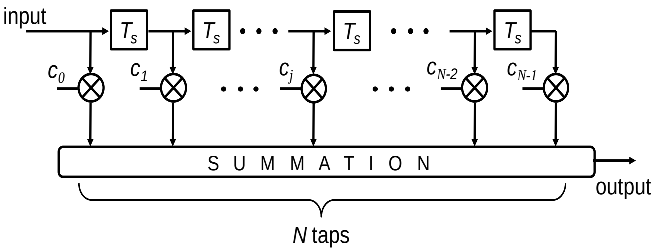


Figure 2. Schematic of a finite impulse response filter.

For CAP-based transmission, we have recently shown that these conventional linear equalizers cannot mitigate the CCI induced by the non-linear phase response of the link [8]. As a result, we have proposed a new equalizer structure, named the CAP equalizer, which is based on conventional FFEs and DFEs, and which can mitigate this crosstalk issue providing great improvements in the link performance. The operation of this equalizer relies on the use of the signals received on both the I- and Q-channels to recover the symbols transmitted on each one of them. Figure 3 illustrates the operation principle of the conventional FFE and DFE equalizer which is applied on each channel independently and our proposed CAP equalizer. The CAP equalizer includes an FFE and a DFE on the main channel as in a conventional structure but in addition, features an FFE and a DFE which are applied on the received signals of the other (crosstalk) channel. The mathematical expressions that describe its operation have been presented in [8] and [11] along with detailed diagrams of the equalizer structure. Here we present simulation and experimental studies that demonstrate the improvements that the use of this equalizer brings in link performance either as a post-equalizer or a pre-equalizer over the conventional FFE and DFE equalizer of the same length.

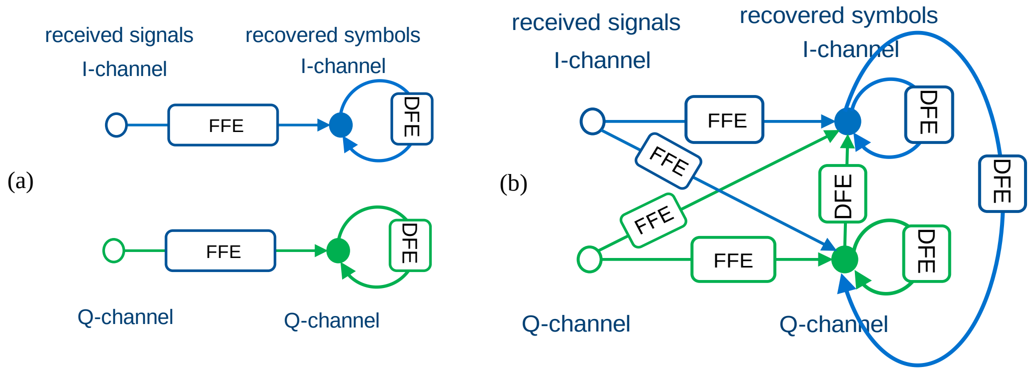


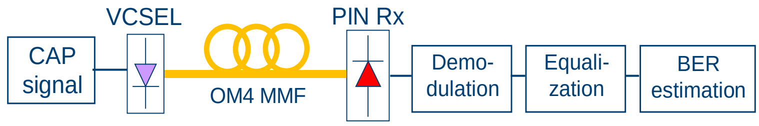
Figure 3. Schematic of the structure of (a) conventional FFE and DFE equalizer and (b) the CAP equalizer.

3. SIMULATION STUDIES

In order to study the performance of the optical links employing the CAP equalizer, a link model is set up based on the parameters of the real components used in the experiments. The basic model is illustrated in Figure 4(a) while in Figure 4(b) the values of the main parameters of the components used in the studies are shown. A rate equation model is used to simulate the VCSEL, a Gaussian response is assumed for the OM4 MMF and a raised cosine response is employed for the receiver. The simulated frequency response of the optical link is shown in Figure 4(c). The link -3 dB bandwidth is found to be ~18 GHz, while the phase response is roughly linear up to 10 GHz. This implies that any CAP-based data transmission over the channel with significant spectrum over 10 GHz will induce significant CCI in the link. This can be demonstrated by plotting the received symbol values on one channel (here the I-channel) when the other channel (here the Q-channel) is operating and when not operating at two different symbol rates (Figure 5). One of them is chosen to be at a low symbol rate [here 9 GBaud → 28 Gb/s, Figure 5(a)] which is within the linear range of the phase response of the link, and one at a higher baud rate [here 28 GBaud →112 Gb/s, Figure 5(b)] which is in the non-linear region. It can be clearly noticed that the operation of the Q-channel significantly affects the values of the recovered symbols at the receiver only for the higher symbol rate of 28 GBaud. This is due to the induced CCI in the link.

To demonstrate the effect of the use of the additional FFE and DFE on the crosstalk channel, a comparative simulation between the conventional and the CAP equalizer structure is performed as described below. A conventional reference equalizer with 20 FFE taps and 20 DFE taps is set up at the receiver. The CAP equalizer structure is then formed by introducing additional taps on the crosstalk channel. Up to 5 additional taps in each part (max 25 FFE taps and 25 DFE taps) are used. The length of the conventional reference equalizer is also increased but here the taps are added to the main channel. In this way, the total number of taps of both equalizers is the same for each additional tap inserted. The error vector magnitude (EVM) of the recovered symbols for 112 Gb/s CAP-16 transmission over 100 m OM4 is calculated for both equalizers as a function of the additional number of taps [Figure 6(a)]. It can be clearly noticed that the introduction of even a small number of taps on the crosstalk channel for the CAP equalizer results in a great improvement in EVM values. On the other hand, for the conventional equalizer no improvement is noticed despite the longer equalizer length.

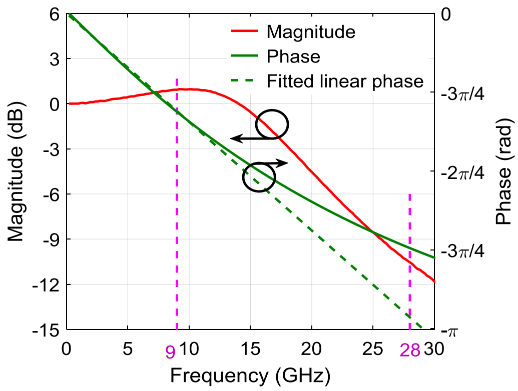
The performance of the 112 Gb/s (28 GBaud) CAP-16 100 m OM4 link is obtained when (i) the conventional and (ii) the CAP equalizer is used at the receiver side. The FFE tap spacing is T/2 for both equalizers while their total length is kept the same to allow fair comparison. For the conventional equalizer, the FFE part comprises 25 taps, while the DFE part 25 taps (50 taps in total). For the CAP equalizer, 20 taps are assumed for the main channel and 5 taps for crosstalk channel for each equalizer part (FFE and DFE, 50 taps in total). A 2^{11}-1 pseudorandom binary sequence (PRBS) is used to generate the training and test data patterns. The data is encoded into CAP-16 symbols (PAM-4 encoding on each channel) which are then randomly re-arranged to form the training pattern. A least mean squares (LMS) algorithm is used to optimise the values of the equalizer tap coefficients. The performance of the link is then tested when the test pattern is transmitted. The test pattern comprises the CAP-16 symbols in the normal order, as generated via the encoding process without any rearranging. Figure 6(b) and (c) show the constellation diagram of the recovered symbols after transmission over the 100 m OM4 MMF when the two equalizers are employed. No noise is included in these to clearly show the symbols recovered in each case. It is clear that the use of the CAP equalizer provides a much better quality constellation diagram, and all symbols can be easily discerned. The conventional equalizer fails to recover all transmitted symbols. The bit-error rate is estimated for the CAP equalizer assuming Gaussian noise with a root mean square (rms) amplitude, that matches the value measured in the experimental studies, and applying the noise enhancement due to the use of the equalizer at the receiver. The plot is shown in Figure 8(b) in the experimental section in order to allow comparison with the experimental data.



(a)

(b)

Component	Response type	-3 dB BW (GHz)
VCSEL	Rate equation based	25
100 m OM4 MMF	Gaussian	24
Receiver	Raised-cosine	30



(c)

Figure 4. (a) Illustration of link model used in the simulation studies, (b) main component parameters and (c) total link amplitude and phase response.

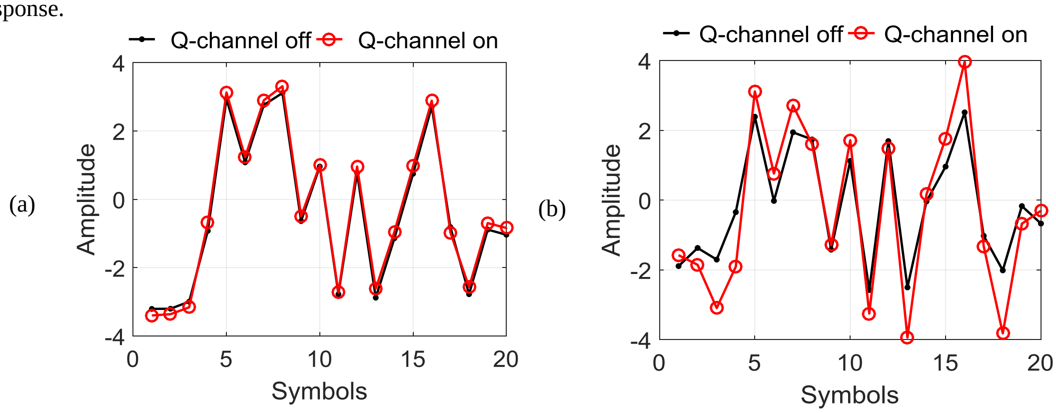


Figure 5. Received symbol amplitude for the I-channel for CAP-16 data transmission over 100 m OM4 when the Q-channel is and is not transmitting data at (a) 9 GBaud (36 Gb/s) and (b) 28 GBaud (112 Gb/s).

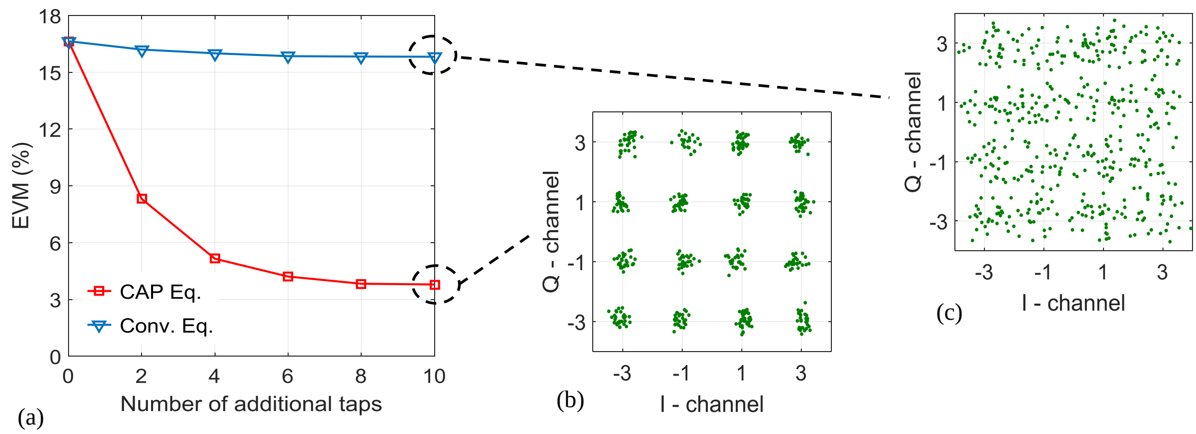


Figure 6. (a) EVM of the received signal for 112 Gb/s CAP-16 100 m OM4 data transmission as a function of the number of additional taps used on each channel for the two types of equalizers and (b-c) noise-free constellation diagrams of the recovered symbols for the longest equalizer considered (50 taps in total on each channel): (b) CAP and (c) conventional equalizer.

4. EXPERIMENTAL RESULTS

An experiment is set up using a multimode 22 GHz 850 nm VCSEL and 100 m OM4 MMF. The experimental setup is shown in Figure 7. The 112 Gb/s CAP-16 modulating signal is generated with an arbitrary waveform generator (AWG) and fed to the VCSEL via an RF amplifier and a bias tee. The emitted light is coupled to 50 µm MMF patchcord via a pair of microscope objectives. A variable optical attenuator (VOA) is used to control the level of received optical power at the receiver. A 30 GHz photodiode and an RF amplifier are used at the receiver end. A real time oscilloscope is used to record the received waveforms. The transmitted data pattern is averaged (> 250 periods) to minimise the effect of noise on the estimation of the equalizer coefficients. Offline processing is used to demodulate the signals, apply equalization and estimate the BER. The conventional equalizer comprises 27 FFE and 27 DFE taps in each channel while the CAP equalizer employs 22 taps on the main channel and 5 taps on the crosstalk for each part (FFE and DFE). Figure 8(a) and (b)Figure 8 show respectively the (noise-free) constellation diagrams when the conventional or CAP equalizer is applied at the receiver. Similarly to the simulation studies, the experimental results show that the CAP equalizer provides clear constellation diagrams enabling the successful recovery of the transmitted symbols, while the conventional equalizer fails at this data rate. The estimated BER is shown in Figure 8(b) along with the simulated curve. The receiver sensitivity to achieve the hard decision forward error correction (HD-FEC) threshold of 3.8×10^{-3} is found to be -1.9 dBm. The respective value obtained via the simulations is -2.4 dBm, demonstrating very good agreement.

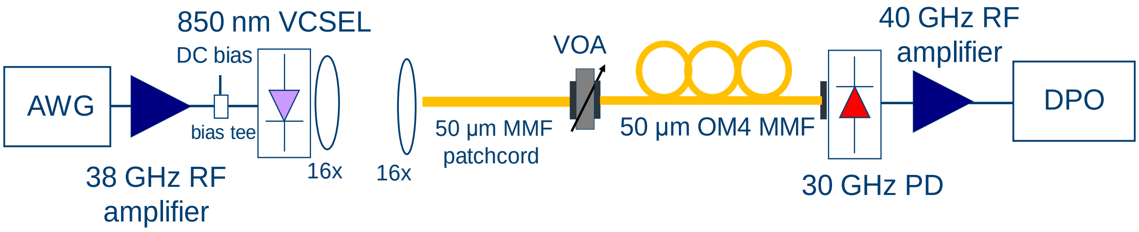


Figure 7. Experimental setup used in data transmission studies.

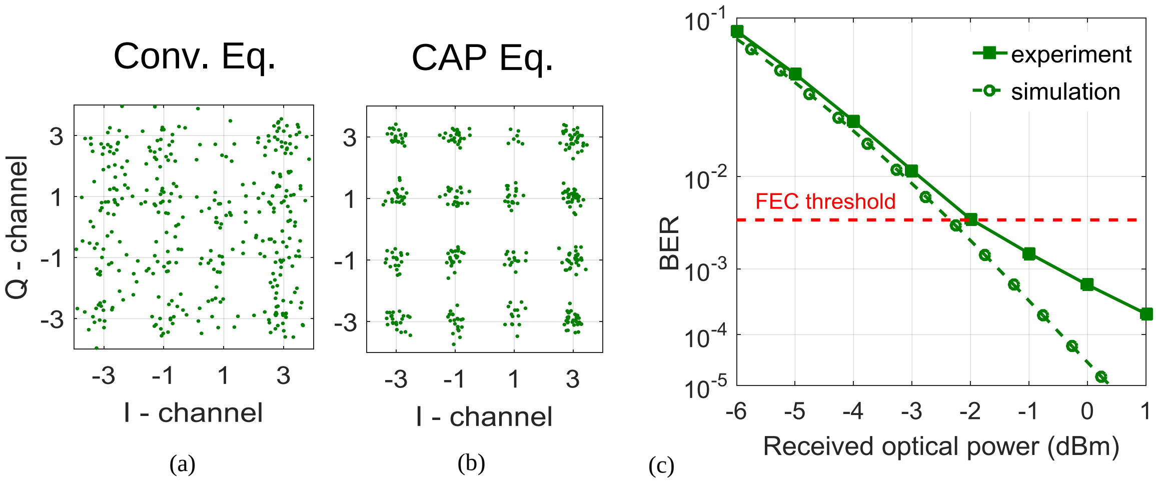
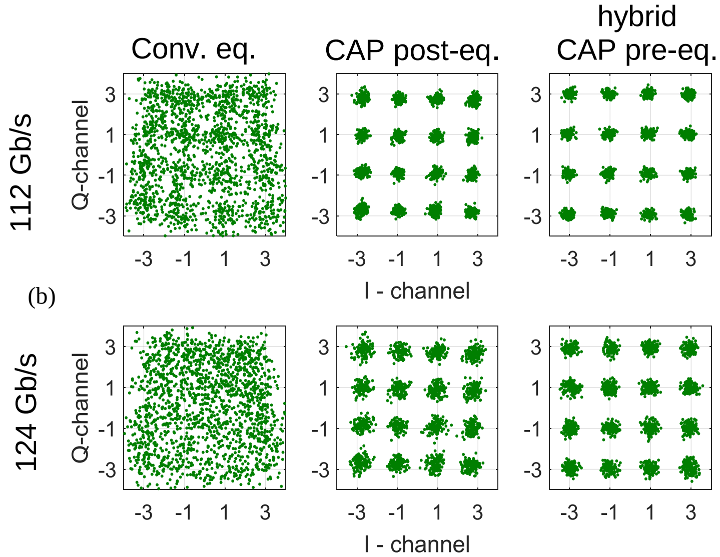


Figure 8. Noise-free constellation diagrams for 112 Gb/s CAP-16 data transmission over 100 m OM4 for the (a) conventional and (b) CAP equalizer and (c) BER curves for the CAP equalizer.

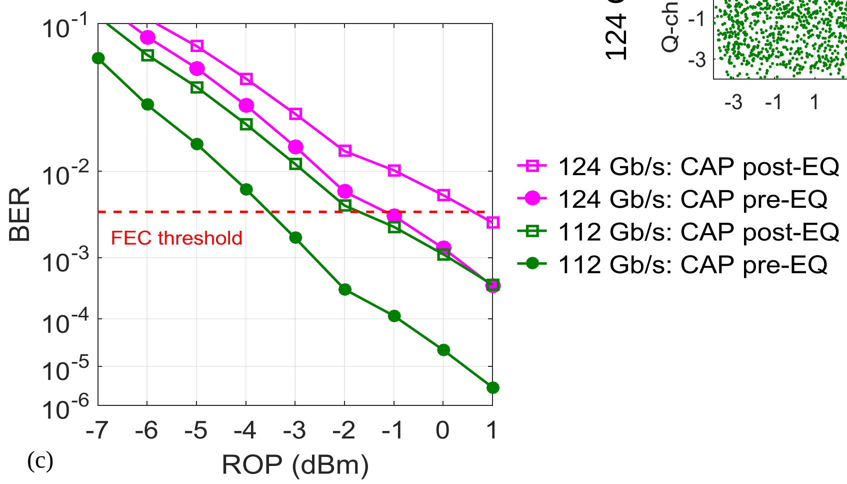
The FFE part of the CAP equalizer can also be applied at the transmitter side of the link as a pre-equalizer. The values of the tap coefficients of the pre-equalizer structure can be found using the values of the CAP post-equalizer. The method is described in greater detail in [11]. Here, in order to enable higher data rates and also allow for flexible implementation, a short (< 5 tap) FFE-based CAP equalizer is applied in addition at the receiver side of the link. Similar link transmission experiments are carried out at 112 Gb/s (28 GBaud) and 124 Gb/s (31 GBaud) when different types of equalizers are used: (i) the conventional equalizer, (ii) the CAP post-equalizer and (iii) the hybrid CAP pre-equalizer. Figure 9(a) summarises the number of taps used in each equalizer part for each type of equalizer used while Figure 9(b) shows the noise-free constellation diagrams for the two data rates and three equalizers studied. It can be clearly observed that the conventional FFE and DFE equalizer fails to recover the transmitted symbols at both data rates and that the hybrid CAP pre-equalizer provides the best performance. The respective BER curves are shown in Figure 9(c), while Figure 9(d) summarises the obtained receiver sensitivity for the 100 m OM4 link. The receiver sensitivity to achieve the HD-FEC threshold is found to be -1.7 and +0.6 dBm for the CAP post-equalizer and -3.5 and -1.2 dBm for the hybrid CAP pre-equalizer for 112 Gb/s and 124 Gb/s respectively. The results demonstrate that the use of the CAP equalizer at the transmitter side provides a significant improvement in receiver sensitivity of ~1.8 dB at both data rates. Such an increase in receiver sensitivity is of great importance in such high-speed links due to the very tight power budget.

Scheme	pre-equalizer channel taps		post-equalizer channel taps				Total equalizer taps per channel
	main FFE	crosstalk FFE	main		crosstalk		
			FFE	DFE	FFE	DFE	
conv. eq.	-	-	31	27	-	-	58
CAP post-eq.	-	-	25	22	6	5	58
hybrid CAP pre-eq.	22	5	3	22	1	5	58

(a)



(b)



(c)

Rx sensitivity for 3.8×10^{-3} BER (dBm)		
Equalizer	100 m OM4 MMF	
	112 Gb/s	124 Gb/s
conv. eq.	x	x
CAP post-eq.	-1.7	+0.6
hybrid CAP pre-eq.	-3.5	-1.2

(d)

Figure 9. (a) Number of taps used for each part of the three equalizers studied for the data transmission of 112 and 124 Gb/s CAP-16 over 100 m OM4 (b) respective noise-free constellation diagrams, (c) estimated BER curves for the operating links (CAP post-eq. and hybrid CAP pre-eq.) and (d) receiver sensitivity for the HD FEC threshold.

5. CONCLUSIONS

A novel low-complexity equalizer structure, named the CAP equalizer, can provide important advantages in the operation of high-speed CAP-based optical links. This equalizer, unlike conventional FFE and DFE equalizers, can mitigate both the ISI and CCI in the link due to a non-ideal link frequency response. It is shown via simulation studies and experiments that the CAP equalizer outperforms the conventional FFE and DFE equalizer of the same length providing important improvements in receiver sensitivity. Single-lane 112 Gb/s and 124 Gb/s CAP-16 data transmission over 100 m of OM4 MMF are achieved with the proposed equalizer structure. The transfer of the FFE part of the CAP equalizer at the transmitter side can offer even greater improvements in link performance. A hybrid CAP pre-equalizer is demonstrated to provide a 1.8 dB improvement in receiver sensitivity at the 124 Gb/s data rate.

6. ACKNOWLEDGEMENTS

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