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50 Gb/s short-reach interconnects with DSP-free direct-detection enabled by CAPS codes

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Abstract: We experimentally demonstrate 50 Gb/s transmission below an uncorrected bit error rate (BER) of 10^{-3} in the C band over a transmission reach that extends from 0 to 20 km using combined amplitude and phase shift (CAPS) codes. The CAPS signal, which is not required to be specifically dispersion compensated for each reach within the 20 km operating range, is amenable for simple direct detection using a single photodetector without any subsequent digital signal processing (DSP). Hence, the presented solution constitutes a potentially attractive low cost solution for mobile Xhaul applications employing single mode fiber interconnects with reaches extending to 20 km. Furthermore, the CAPS signaling is compared to other modulation schemes all delivering 50 Gb/s and is found to outperform on-off-keying (OOK), 4-level pulse amplitude modulation (PAM4) and dispersion precompensated OOK in terms of dispersion tolerance. At a lower reach of 10 km, the maximum bit rate that can be achieved using CAPS coding at a BER below 10^{-3} is found to increase to 67 Gb/s. In addition, using the same testbed, we experimentally tested the IQ duobinary modulation format, which is an alternative format that approximates the CAPS transmitted waveforms in order to omit the need for a power consuming digital-to-analog converter (DAC) to generate the transmitted waveforms at the expense of slightly worse dispersion tolerance. Though the IQ duobinary format can be in principle generated using a simple DAC-less analog transmitter, our proof-of-concept experiment used a DAC to emulate the analog transmitter by generating the corresponding transmitted waveforms due to unavailability of all required analog parts. The IQ duobinary format was found experimentally to enable 50 Gb/s over a reach of ~17 km; that is slightly less than a CAPS signal at the same bit rate. Finally, we verified the excellent performance of the CAPS signaling in an ASE-limited regime where the CAPS signal achieved very low OSNR penalty after 10 km relative to OOK in back-to-back.

OCIS codes: (060.2330) Fiber optics communications, (060.4080) Modulation, (060.2360) Fiber optics links and subsystems.

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1. Introduction

The capacity in the access network, either fixed or mobile, continues to grow at a dramatic rate: global Internet traffic in 2021 will be 127 times the volume of the entire global Internet in 2005 [1], generating a burgeoning capacity demand also in the subsequent aggregation segments. This demand is even more urgent considering that busy-hour traffic is growing more rapidly than the average one (growth rates between 2016 and 2021 are 4.6 and 3.2 for busy-hour and average traffic, respectively), leading to bandwidth resources overprovisioning. The ever increasing number of mobile subscriptions (63 percent of IP traffic by 2021 [1], with 5G broadband subscriptions exceeding half a billion by the end of 2022 [2]), confirms this trend and, more importantly, is causing a deep transformation of the aggregation network architecture by accelerating the evolution towards a converged infrastructure, usually referred to as Xhaul, able to support both backhaul and fronthaul services [3, 4]. Today DWDM systems working in the 1550 nm wavelength region can satisfy the capacity requirement of 5G transport networks but the inadequacy of the current transmission and switching technologies, based on coherent 100 Gbit/s Dual Polarization Quadrature Shift Keying (DP-QPSK) and Wavelength Selective Switches (WSS), respectively, to meet cost and energy consumption figures adequate to the Xhaul network has already been noted [5]. This work will focus on the transmission aspects, investigating the possibility of developing cost effective and high speed (50 Gbit/s and beyond) transmission techniques, suitable for the Xhaul application space, based on optical direct detection [6]. The use of direct detection aims at avoiding the DSP, which contributes significantly to the cost (up to 70% [7]) and energy consumption (tens of Watts [8]) of DP-QPSK coherent transmission interfaces. In a Xhaul network, the allowed distance between the antenna and baseband processing site varies with the adopted protocol split for the fronthaul interface [9] and the service type [10]. The highest distance values for these links are in the order of 20 km and are expected to occur in centralized radio access networks (C-RANs), where operators concentrate and possibly virtualize baseband or packet processing functionalities in a limited number of central offices or data centers (hubs). Such reaches are achievable with optical direct detection, provided that it is possible to counteract fiber chromatic dispersion effects that are detrimental at 50 Gbit/s, and beyond. Solutions based on passive optical devices, for example Dispersion Compensating Fiber (DCF), are common in metro and backbone networks, but increase the link loss, which is critical in access and aggregation networks, where it is desirable to minimize the number of optical amplifiers. Moreover, they require maintaining an equipment inventory and spare parts at each node, increasing the total cost of ownership (TCO).

With the constraint of avoiding the DSP that is capable of electrical dispersion compensation (EDC) in a coherent transponder, the optical components industry is considering multilevel Pulse Amplitude Modulation (PAM) formats and Discrete Multi-Tone (DMT) as direct detection modulation formats able to bridge the 20 km distance. However, given a bit rate of 50 Gb/s, PAM-4 at 25 Gbaud can only achieve a reach of about 10 km while accepting a relatively large optical power penalty with respect to a back-to-back OOK system (4 dB in simulation [6] which increases to ~7 dB as depicted by our experimental results in the current manuscript). Increasing the modulation order further to use for instance PAM-8 can further extend the reach while compromising the optical power link budget. Moreover, while PAM-4 is practical as a solution, PAM-8 is not because of its higher susceptibility to transmission impairments [11] and the more stringent bit resolution required for signal converters. The achievable performance with DMT is comparable to the one that can be attained with PAM-4 and the amount of DSP required at the transmitter and receiver is significant [12].

A possible alternative to OOK or PAM is using the combined amplitude phase shift (CAPS) codes for combating chromatic dispersion [6]. CAPS-3 is an example modulation format which is relatively simple to generate by means of an IQ modulator driven by two digital-to-analog converters, can be direct detected and is able to defeat a significant amount of chromatic dispersion over a broad range without requiring any change in the modulation parameters and without the need for any digital signal processing at the receiver side. CAPS was proposed in [13] as a family of optical line codes exhibiting a high tolerance to chromatic dispersion and requiring a simple direct detection receiver. Later in [14], the effectiveness of the CAPS-3 code was experimentally verified in a preliminary experiment at 25 Gb/s. Furthermore in the simulation work of [6], CAPS-3 waveforms were approximated by the so-called IQ duobinary modulation format in which the transmitted waveforms can be generated by means of a scheme based on analog electrical filters and delay lines, which avoids the use of energy consuming digital to analog converters to drive the IQ modulator. The simplified transmitter architecture of the IQ duobinary format comes at the expense of slightly lower reach compared to CAPS-3 as was proved via simulations in [6].

In this work, we perform a new experimental demonstration of CAPS-3 and IQ-duobinary signaling at 50 Gb/s and beyond; that is more than twice the bit rate previously reported in the preliminary experiment in [14]. More specifically, we perform an extensive comparison between various modulation schemes all delivering a fixed bit rate of 50 Gb/s in terms of their required received optical power at various reaches. The CAPS-3 format is found to outperform OOK and PAM4 signaling schemes in terms of the maximum reach. In addition, the 50 Gb/s CAPS-3 signal is found to achieve an excellent dispersion tolerance over a broad range of transmission distances (0 to 20 km) without having to specifically compensate dispersion depending on the nominal target reach as in CD precompensated OOK, i.e. without the need for modifying the modulation parameters of the CAPS-3 signal. Furthermore, we obtain the maximum achievable bit rate that can be obtained at various reaches using the CAPS-3 signaling. Up to 67 Gb/s was successfully accomplished below BER of 10^{-3} after 10 km using CAPS-3. In addition, we assess the IQ duobinary format using the same experimental testbed employing a DAC due to unavailability of all required analog components though it can be in principle generated by a DAC-less analog transmitter. The 50 Gb/s IQ duobinary signal is found to achieve a reach of 17 km; that is slightly lower than CAPS-3 which agrees with simulation results in [6]. Finally, we perform an OSNR sweep to compare different modulation formats in an ASE-limited regime.

The paper is organized as follows. Section 2 explains the basic principles and modulation parameters of both the CAPS coding and its approximate analog implementation, denoted hereafter IQ duobinary. In section 3, the experimental testbed employed is depicted followed by the detailed experimental results in section 4. We finally conclude in section 5.

2. Principles of CAPS coding and its approximate analog implementation

In the linear regime, accounting only for the group velocity dispersion (GVD), the transfer function of a single mode fiber of length L can be very well approximated as [15]

$$H(f) = e^{j\alpha_d f^2} \tag{1}$$

where

$$\alpha_d = \pi D L \lambda^2 / c \tag{2}$$

c being the speed of light, λ the wavelength, and D the chromatic dispersion parameter (usually given in ps/(nm.km)).

Chromatic dispersion causes pulse broadening and can severely limit the reach at a given bit rate. As known, a possible countermeasure to chromatic dispersion is linear chirping. A linearly chirped pulse can be expressed as

$$s_{in}(t) = x(t) e^{jat^2} \tag{3}$$

where $x(t)$ is the unchirped pulse. Choosing the chirp parameter a such that $a\alpha_d = \pi^2$ it can be shown that, at the output of a fiber with transfer function (1), the pulse (3) becomes *exactly* [13]

$$s_{out}(t) = \sqrt{\frac{\pi}{|\alpha_d|}} e^{-j\left(\frac{\pi^2}{\alpha_d}t^2 - \frac{\pi}{4} sgn\alpha_d\right)} X\left(-\frac{\pi}{\alpha_d}t\right) \quad for\ a\alpha_d = \pi^2 \tag{4}$$

where $X(f)$ is the Fourier transform of $x(t)$. For example, the chirped ideal NRZ pulse of width T

$$s_{in}(t) = rect\left(\frac{t}{T}\right) e^{jat^2}, \tag{5}$$

introducing the dimensionless chromatic dispersion index

$$\gamma \triangleq \frac{\alpha_d}{\pi^2 T^2}, \tag{6}$$

becomes

$$s_{out}(t) = \sqrt{\frac{|\gamma|}{\pi}} e^{-j\left(\frac{1}{\gamma}\left(\frac{t}{T}\right)^2 - \frac{\pi}{4} sgn\gamma\right)} \sin c\left(\frac{t}{\pi\gamma T}\right). \tag{7}$$

As can be seen, for $\gamma = \frac{1}{k\pi}$, $k = 1, 2, \ldots$, there is no intersymbol interference (ISI) when sampling at $t = nT$. However, using pulses whose width does not exceed the symbol duration T, the maximum value of γ for which ISI can be avoided is $\gamma = 1/\pi$. Hence, for a standard fiber of length 20 km with $D = 17\ ps/nm/km$, from (6) we have that chirping is useful only for bit rates less than about 20 Gb/s. If we were allowed to use longer pulses, we could design a pulse that, when properly chirped, would allow to avoid ISI for any value of γ. The price to pay would be that the pulse width should increase with the square of the bit-rate, that is linearly with the chromatic dispersion index γ. Indeed, suppose that for a given value of $\gamma = \gamma_1$ the output pulse (4) avoids ISI. Then, for $\gamma = \kappa\gamma_1$, the output pulse corresponding to $s_{in}^{'}(t) = s_{in}(t/\kappa)/\sqrt{\kappa}$ would still be (4) when properly adjusting the chirp parameter a. Of course, for $\kappa > 1$ the width of the transmitted pulse now needs to exceed the symbol time T, so that generating a pulse amplitude modulated (PAM) signal with supporting pulse $s_{in}^{'}(t)$ is only feasible through coding. These codes have been devised in [13] and were later named combined amplitude-phase shift (CAPS) codes [16]. Using a supporting pulse $s_{in}(t)$ of length $(n+1)T$ corresponds to an order-n CAPS code. As an example, a possible supporting pulse for an order-3 CAPS code is shown in Fig. 1, where the parameters α and β can be chosen to optimize performance. Note that in CAPS coding the information symbols are also differentially encoded in order to further halve the signal bandwidth.

The effectiveness of an order-3 CAPS code was experimentally demonstrated at 25 Gb/s in [14] using a digital-to-analog converter (DAC) for implementing the code, while a simpler implementation not requiring a DAC was proposed in [6]. According to [6], a CAPS-3 signal can be approximated by associating a quadrature component to a duobinary coded signal. Such a component is given by two attenuated replicas of the duobinary signal itself, respectively anticipated and delayed by a symbol time T. This novel format was named IQ-duobinary and a block diagram for its generation is reported in Fig. 2. Here, $g_2 = \rho g_1$ with $0.1 \le \rho \le 0.3$, such that the power associated to the quadrature component is almost negligible with respect to the in-phase one. The higher ρ the larger the distance that can be bridged but also the higher the penalty at intermediate distances. However, increasing ρ the improvement becomes progressively smaller, such that there is no practical advantage using values greater than about 0.3. The Mach-Zehnder modulator (MZM) in the in-phase branch does not necessarily need to be driven between two transmission maxima. A comparison between the MZM's electrical drive signals obtained by a CAPS-3 code and the IQ-duobinary ones is shown in Fig. 3. Simulation results in [6] show that, given a 3 dB penalty with respect to a back-to-back OOK system, a CAPS-3 code can bridge ~20 km at a bit rate of 50 Gb/s, while an IQ-duobinary signal tolerates dispersion corresponding to about 17 km. Hereafter we report about the experimental results obtained in the laboratory at 50 Gb/s and beyond.

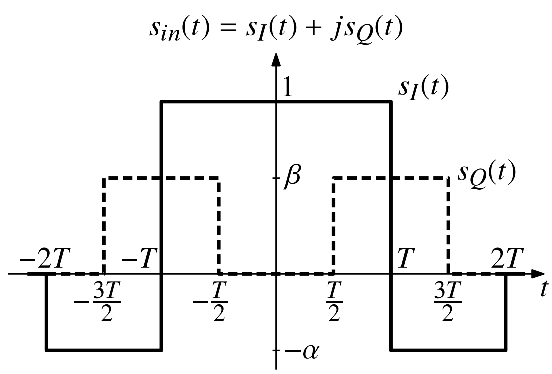

Fig. 1. CAPS-3 supporting pulse.

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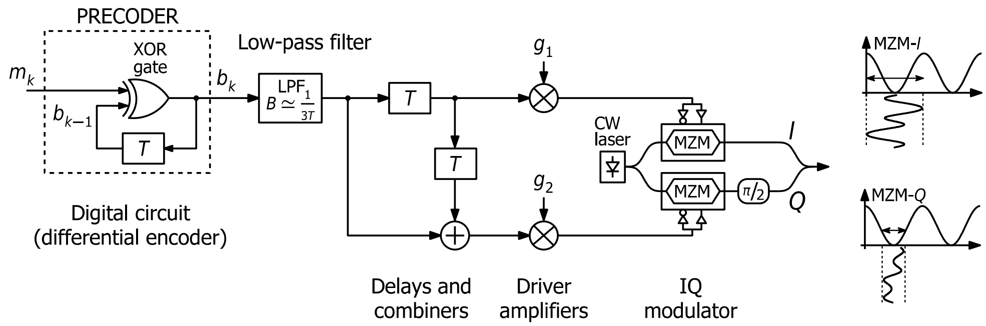

Fig. 2. IQ-duobinary transmitter.

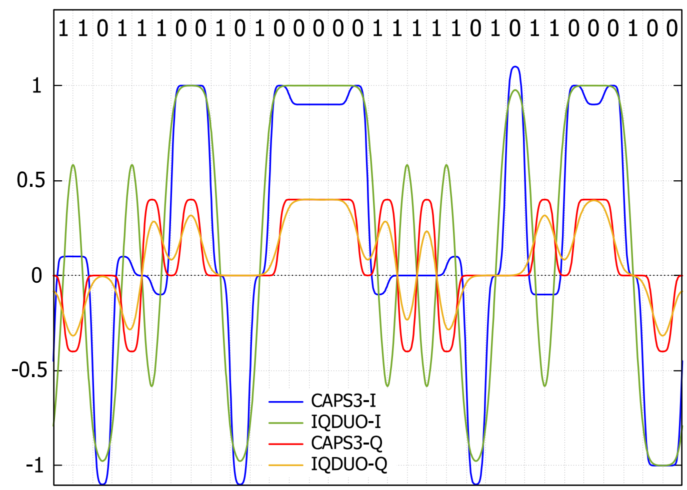

Fig. 3. MZM's electrical drive signals for the given binary information sequence. The amplitudes are relative to the bias voltage and are normalized to the MZM V_π.

3. Experimental setup

Figure 4 depicts the experimental setup used to verify the CAPS-3 line codes and compare it against other transmission techniques, all targeting 50 Gb/s and beyond over 20 km reach. The testbed comprises a 15.5 dBm continuous wave (CW) laser which feeds a 25 GHz single polarization in-phase and quadrature (IQ) modulator whose child Mach-Zhender modulators (MZM) are both biased at the null transmission point of their transfer function and the parent MZM is biased at its quadrature transmission point. The two electrical signals driving the IQ modulator are generated from two channels of a digital-to-analog converter (DAC) running at 84 GSa/s with 3-dB bandwidth of 25 GHz after being amplified by two RF amplifiers each with ~40 GHz 3-dB bandwidth.

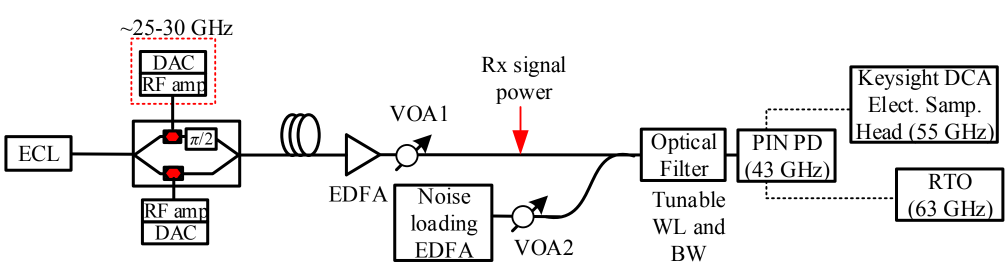

Fig. 4. Experimental setup.

Throughout the experiment, the DAC sampling rate is kept fixed at 84 GSa/s and the symbol rate is changed by varying the numbers of samples per symbol, i.e. the over sampling factor. For the CAPS-3 and the IQ duobinary cases, the I and Q signals are generated according to the theory presented in the previous section which was previously detailed in [6, 13]. The modulated signal is then launched into standard single mode fiber with varying lengths from 0 to 20 km. At the output of the fiber, the received signal is optically pre-amplified by means of an Erbium doped fiber amplifier (EDFA) and attenuated using VOA1 to set the received signal power to the desired level. The second EDFA and VOA2 were only used for noise loading to sweep the OSNR and study the system performance in an ASE limited regime. When noise loading was performed, an optical filter was used prior to photodetection with its optical bandwidth set to twice the baud rate in order to reject the out-of-band ASE noise. Photodetection is performed by a PIN photodiode having 3-dB bandwidth of 43 GHz and responsivity of 0.5 A/W. Finally, the photocurrent is fed to the electrical sampling head of a Keysight digital communication analyzer (DCA) to measure eyediagrams to assess qualitatively the received signal integrity. Alternatively, the photocurrent is sampled at 160 GSa/s by a real-time oscilloscope having an analog bandwidth of 63 GHz to perform error counting offline. Prior to error counting, no DSP is performed on the received waveforms; we only perform timing recovery to find the optimum decision point within the symbol duration as well as finding the optimum decision threshold. Finally, it is noteworthy that the use of an EDFA as a preamplifier prior to photodetection was essential in the testbed since it comprised PIN photodiodes without subsequent transimpedance amplifiers (TIAs) however, EDFA-less operation is achievable if PIN photodiodes equipped with TIAs with sufficient 3-dB bandwidth are employed for photodetection.

4. Experimental results

In a first set of measurements, receiver sensitivity at BER = 10^{-3} is measured and compared for various transmissions schemes as a function of the transmission distance, in a thermal noise limited regime, assuming as a reference the OOK sensitivity in back-to-back configuration. All modulation schemes compared in Fig. 5 deliver a bit rate of 50 Gb/s. As depicted in Fig. 5, the maximum achievable distance for OOK is 6 km obtained while having to increase the received optical power by 4 dB relative to back-to-back. On the other hand, PAM-4 at 25 Gbaud is capable of reaching at most 10 km with a severe optical penalty of more than 7 dB with respect to back-to-back OOK signaling. The performance of 50 Gb/s CAPS-3 has been evaluated considering two different configurations (corresponding to different values of the α and β parameters): in a first configuration (α = 0.15, β = 0.6, red crosses), CAPS-3 shows only 2 dB penalty up to 15 km and can reach up to 16 km at the expense of higher penalty of 4 dB. Even longer distances can be reached by reconfiguring the modulation parameters to α = 0.9, β = 1.4 (black circles), enabling a transmission reach up to 20 km with 4 dB of penalty at the expense of an increased penalty at very short distances 0-5km due to the introduced pre-distortion. IQ-duobinary (triangles) with an amplitude ratio 0.55 between the I and Q electrical driving signals (corresponding to a parameter ρ = 0.275), digitally emulated through the DAC, shows very good agreement with simulations, with a very low (or even negative) penalty up to 15 km. The penalty increases for longer distance, reaching 8 dB at a maximum reach of 17 km. Figure 5 also reports for comparison an example of a digitally CD-precompensated OOK for a nominal distance of 20km. The CD precompensation is performed offline on the transmitted waveform prior to loading into the DAC which drives the IQ-modulator. As expected, penalty-free performance is obtained only in a limited range close to the nominal compensated distance of 20 km, while the penalty rapidly increases in case of under- or over-compensated lengths. In contrast to the CD precompensated signal, both variants of the CAPS-3 signal exhibited dispersion tolerance over a much broader distance range without needing to change the modulation parameters; a major advantage of the CAPS-3 signaling. In order to further visualize the comparison between the modulation schemes of Fig. 5, we compare in Table 1 the received eye diagrams of different modulation schemes at various reaches which were obtained directly via the DCA shown in the experimental testbed. The eye diagrams further confirm the superior dispersion tolerance of the CAPS-3 and IQ duobinary signals over a broad range of transmission distances. In order to make the comparison between these various modulation formats more complete, we should also account for the difference in transceiver architectures in addition to the difference in dispersion tolerance. All of these formats considered in Fig. 5 and Table 1 require a simple DSP-free single photodetector receiver. However the transmitter of CAPS3, IQ duobinary and CD precompensated OOK formats employs an IQ modulator with two drive signals to manipulate the amplitude and phase of the modulated light to combat chrmoatic dispersion. On the other hand, uncompensated OOK and PAM4 utilize a simpler transmitter comprising an intensity modulator (e.g. a Mach-Zhender modulator, or an Electroabsorption modulator) with a single drive signal at the expense of much limited dispersion tolerance as confirmed by Fig. 5 and Table 1.

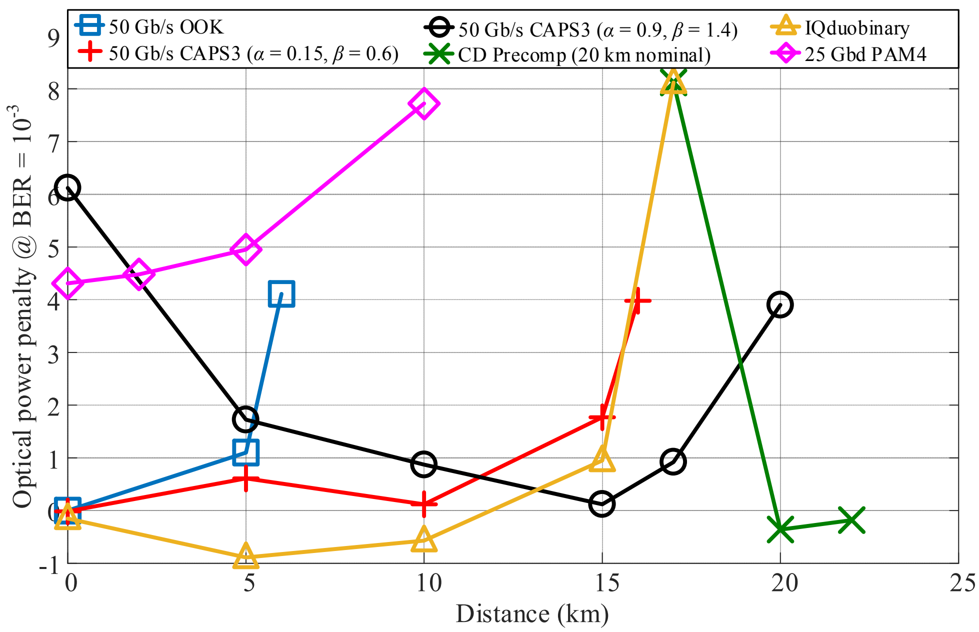

Fig. 5. Optical power penalty at BER = 10-3 for various modulation schemes all delivering a bit rate of 50 Gb/s. The optical power penalty is calculated relative to a reference required received optical power of OOK in back-to-back to achieve BER of 10-3.

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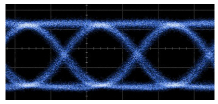
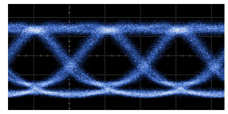
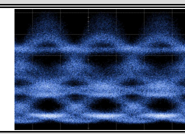
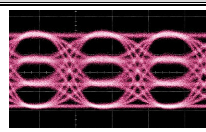
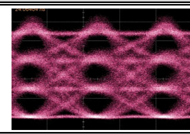
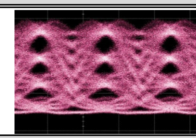
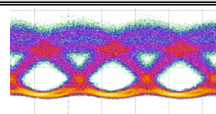
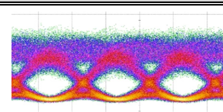
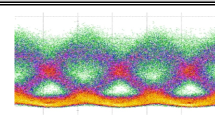
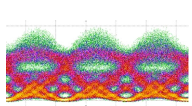
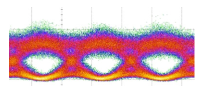
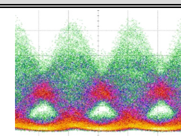
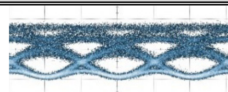
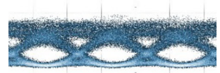
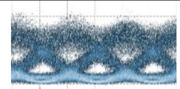
Table 1. Received eye diagrams of different modulation schemes all delivering 50 Gb/s at different reaches.

	B2B	2 km	5 km
OOK			
	B2B	5 km	10 km
PAM4			
	B2B	10 km	15 km
CAPS3 (α = 0.15, β = 0.6)			
	B2B	10 km	20 km
CAPS3 (α = 0.9, β = 1.4)			
	B2B	10 km	15 km
IQ-Duobinary			

In a second set of measurements, we focus on the performance of the CAPS-3 signals for varying bit rates at multiple reaches. Figure 6 shows the measured BER versus bit rate curves for the two different configurations of the CAPS-3 signals (α = 0.15, β = 0.6 and α = 0.9, β = 1.4) at three different reaches of 10, 15 and 20 km. At 10 km, the CAPS-3 signal enables transmission rate of 68 Gb/s below the HD-FEC threshold of 3.8 × 10-3. At 20 km, up to 51 Gb/s can be transmitted at BER of 2.8 × 10-3 (below HD-FEC) using the CAPS-3 code.

Finally we have conducted some measurements of the system performance in ASE-noise limited regime, to assess the performance of OOK, PAM-4 and CAPS-3 while sweeping the optical signal-to-noise power ratio (OSNR) in case optical amplification is employed to boost the receiver sensitivity. A noise loading stage has been exploited to increase the amount of ASE noise coupled with the signal under test as was previously shown in the experimental testbed in Fig. 4. In addition, a subsequent optical filter, with an optical bandwidth set equal to twice the baud rate of the signal under test, is employed after noise loading to reject the out-of-band ASE noise prior to photodetection. The optical power at the photodetector input has been maintained high such that the impact of receiver thermal noise can be neglected for this measurement. The experimental measurements reported in Fig. 7 confirm that PAM-4 is much more prone to OSNR degradation compared to OOK and CAPS-3, with more than 10 dB OSNR penalty relative to OOK in back-to-back. Moreover, the OSNR sensitivity of the CAPS-3 signal does not deteriorate even after 10 km of transmission; it rather achieves a very reasonable OSNR penalty (~2 dB) relative to the OOK modulation in a back-to-back setting.

5. Conclusion

In C band short reach (< 20 km) 50 Gb/s interconnects for mobile Xhaul applications, chromatic dispersion is the primary impairment since there is no optical amplification to compensate for the DCF loss, neither it is advisable to design the dispersion map individually

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for each link. Low cost DSP-free simple direct detection is very attractive for this application segment. Legacy 50 Gb/s OOK cannot provide the desired reach and hence 25 Gbaud PAM4 at half the required bandwidth is being discussed. Verified by our experimental results, PAM4 can only achieve 10 km reach while accepting a large 8 dB optical power penalty with respect to a corresponding back-to-back 50 Gb/s OOK system. In this paper, we presented and experimentally demonstrated the CAPS-3 scheme; a dispersion tolerant modulation format that can achieve the desired 20 km reach while maintaining a low cost DSP-free direct detection and without having to change the modulation parameters depending on the exact desired reach. In addition, the IQ duobinary format, that approximates the CAPS-3 signal and can be generated using a simpler DAC-free analog transmitter, was experimentally shown to bridge ~17 km, which is slightly worse than a corresponding CAPS-3 signal. In conclusion, the CAPS-3 signal which requires an IQ modulator driven by a two channel DAC provides the desired 20 km reach at 50 Gb/s whereas its approximation; the IQ duobinary format, employs a simpler and more power efficient DAC-free transmitter at the expense of slightly lower reach (17 km), hence it is the more favoured solution. Furthermore, our experimental results show that both formats achieve much better dispersion tolerance compared to dispersion uncompensated OOK and PAM4 at the expense of a more complex transmitter structure (an IQ modulator as opposed to a single intensity modulator). Nonetheless, the DSP-free single photodetector receiver of both CAPS-3 and IQ duobinary is as simple as OOK and PAM4. Compared to dispersion precompensated OOK which can utilize an IQ modulator to achieve any desired reach but operates only at that specific reach unless CD precompensation parameters are modified, the 50 Gb/s CAPS-3 and IQ duobinary formats achieve a broader operating range ranging from 0 to 20 and from 0 to 17 km, respectively.

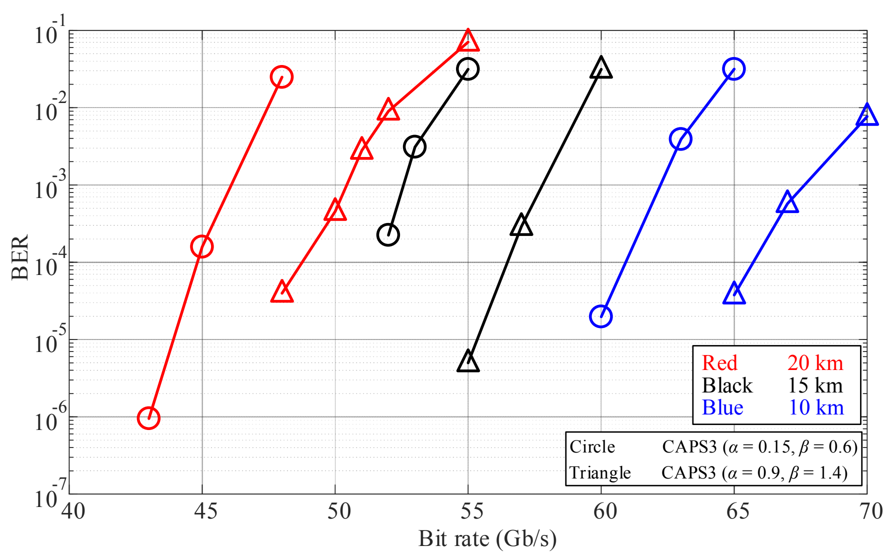

Fig. 6. BER versus bit rate for CAPS-3 signals with two different (α,β) parameters at reaches of 10, 15 and 20 km.

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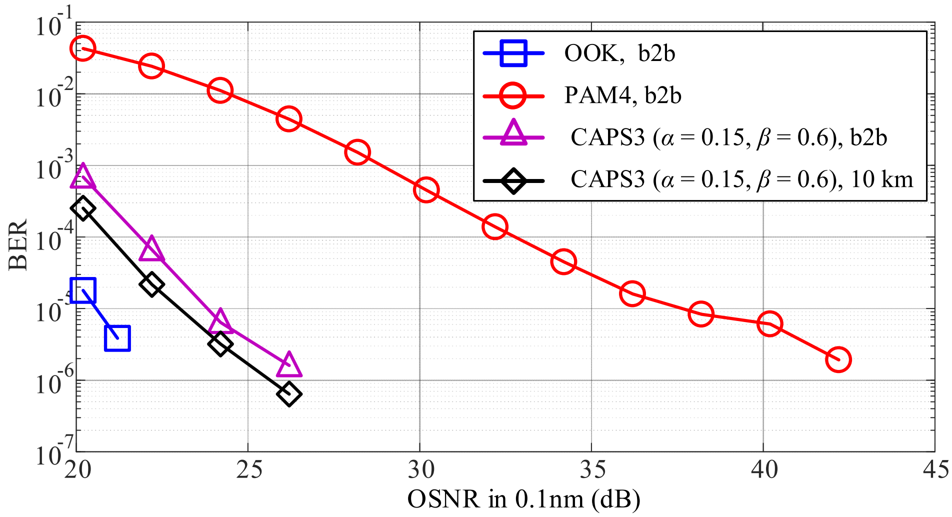

Fig. 7. BER versus OSNR of various modulation schemes when the received signal power is set to 2 dBm, i.e. the system is operated in ASE noise limited regime rather than a thermal noise limited scenario.

6. Acknowledgement

This work was partially supported by the EC through the H2020 METRO-HAUL project (g.a. 761727).