# Experimental Evaluation of PAM and Polybinary Modulation for Intra-DCI Optical Lanes with up to 300 Gbit/s Net Bitrates

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**Abstract:** We experimentally test PAM and polybinary modulation in a wide range of symbol rates, as potential candidates to realize next-generation optical lanes. 306-Gbit/s bitrate is demonstrated with 140-GBd PAM-6 signal at sensitivity −17.9-dBm with EDFA-preamplifier. © 2022 The Author(s)

## 1. Introduction

To meet growing demands of inter-data center interconnects (DCIs), short-reach transmission specifications already today aim at 800 Gbit/s optics [1], with rates exceeding 1 Tbit/s in sight (e.g., 1.6TbE [2]). Demanding cost targets make intensity modulation and direct detection (IM/DD) the preferred solution for up to 2 km DCIs. Consequently, lanes providing at least 200 Gbit/s [3] are needed to keep low lane count, which is critical for reasons such as yield, cost, power consumption and package pinout [4,5]. Further, digital signal processing (DSP) has become an essential part of today's optical transmission systems. It provides not only an efficient way to compensate for system impairments but also allows for a flexible choice of a modulation format. Both pulse amplitude modulation (PAM) and polybinary modulation schemes have the potential to support next-generation optical lanes providing net bitrates beyond 200 Gbit/s. A higher line rate can be achieved by increasing the number of PAM levels while keeping the symbol rate constant. Alternatively, polybinary filtering [6], which gives rise to spectral compression, can be applied to a conventional binary (PAM-2) signal. This in turn allows to increase symbol and line rates in a bandwidth-limited system. Which of the schemes is better to realize high-speed optical lanes – the building blocks of future DCIs?

To answer this question, we investigate PAM and polybinary modulation schemes, using a high-symbol rate IM/DD system transmitting over 2 km standard single mode fiber (SSMF). The system employs dispersion compensation since the grating couplers in the modulator under test have limited bandwidth, working only in C-band. Nonetheless, the optical chip may operate over the entire telecom band [7] thus promising realization of a similar system also over uncompensated links in O-band. Sensitivities and information rates are compared over a wide range of symbol rates for various modulation formats: PAM-2, -3, -4 and -6, as well as duo-, tri- and tetrabinary. Net bitrates exceeding 300 Gbit/s are achieved with a 140 GBd PAM-6 assuming a hard-decision (HD) forward error correction (FEC) code with rate 0.8750 and a 152 GBd PAM-6 signal employing a soft-decision (SD) FEC code with rate 0.7932, while tetrabinary supports up to 264 Gbit/s net bitrate at 280 GBd with HD FEC.

## 2. Experiment

Fig. 1(a) shows the experimental setup. The transmitter is based on Polariton Technologies' ultra-broadband plasmonic Mach-Zehnder modulator (MZM, see inset in Fig. 1), which has been demonstrated in [8]. The modulator

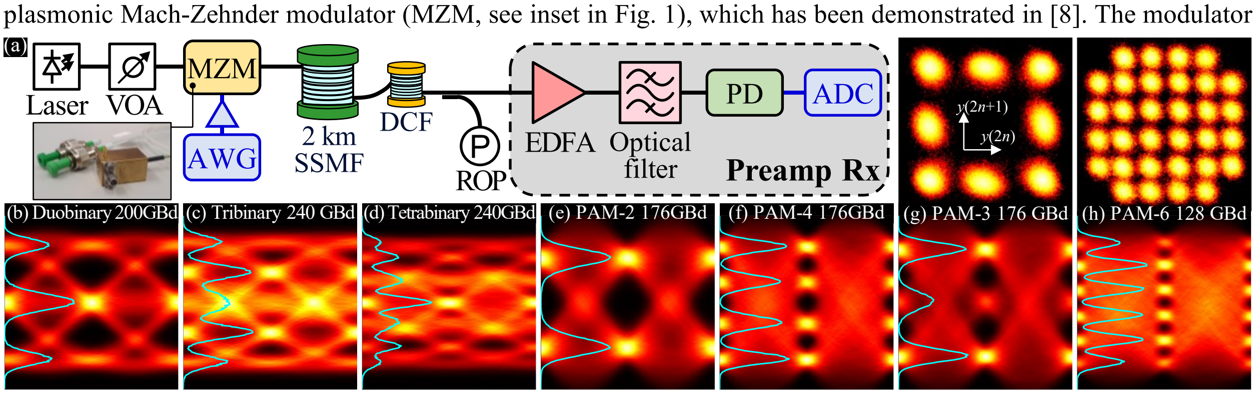


Fig. 1. (a) Experimental setup. (b-h) Eye diagrams of the tested modulation formats at selected symbol rates. Constellation diagrams corresponding to eye diagrams (g,h) were obtained by plotting odd $y(2n+1)$ versus even received symbols $y(2n)$ for integer $n$ representing index over received PAM-3/6 symbols $y$, consistent with the method employed for bit encoding/decoding.

has a 3 dB bandwidth >110 GHz when packaged, a static extinction ratio of >28 dB, a $V_\pi$ of 8.3 V, and a fiber-to-fiber insertion loss of ≈18 dB (which, however, has a potential for significant future reduction [9]). The electrical signal fed to the modulator originates from a 256 GS/s (S=sample) arbitrary waveform generator (AWG) with ≈65 GHz 3-dB analog bandwidth followed by an 11 dB driver amplifier with ≈70 GHz bandwidth. The overall bandwidth of the modulated signal after applying pre-emphasis is limited to ≈72 GHz. The optical carrier is provided from an external cavity laser source emitting at 1532 nm with a power of more than 10 dBm. A variable optical attenuator (VOA) between the laser source and the modulator is used to vary the optical power launched to the modulator and thus also the link. The modulator is biased slightly below the quadrature point to reduce the carrier and improve extinction ratio, and to increase preamplifier gain for the signal. The resulting slight nonlinearity due to off-quadrature bias is compensated by a nonlinear receiver DSP. No booster amplifier is used at the transmitter. This results in a small optical launch power into the fiber and necessitates presence of a preamplifier at the receiver. The optical signal is transmitted over 2 km SSMF, while the dispersion accumulated in the fiber is compensated by a matched dispersion compensating fiber (DCF). Received optical power (ROP) is measured at the input to the preamplifier, which is an erbium-doped fiber amplifier (EDFA) with approximately 35 dB of small-signal gain and 4 dB noise figure. The amplified signal passes through a 1.5 nm optical filter and is detected using a 100 GHz *p-i-n* photodiode (PD) without transimpedance amplifier. The electrical signal is sampled by a free-running 256 GS/s analog-to-digital converter (ADC) with an 84 GHz anti-aliasing brick-wall filter.

For PAM signals under test, the source entropy, $H$, is 1, 1.5, 2 and 2.5 bit/sym (sym=symbol) for PAM-2, -3, -4 and -6 respectively. Practical PAM-3 and -6 is constructed by mapping, respectively, $k$=3 bit onto a QAM-8 (arranged into a 3×3 grid without the center point, c.f., Fig. 1(g), with Gray mapping around the perimeter) or $k$=5 bit onto a QAM-32 constellation (6×6 grid without four corner points, c.f., Fig 1(h), with quasi-SU bit mapping [10, Fig. 15(a)]), and alternately transmitting each constellation dimension over two consecutive timeslots. This approach leads to a small source entropy reduction ($\log_2(M)-k/2\approx 0.085$ bit) below the source entropy of theoretical PAM-$M$. The transmitted symbols are upsampled to 256 GS/s and pulse-shaped using a raised-cosine filter with a roll-off of 0.1. On the receiver side, the signal is resampled to 2 S/sym (Sps) and out-of-band noise is filtered out. Next, a $T$/2-spaced Volterra nonlinear feedforward equalizer followed by a $T$-spaced decision feedback equalizer (DFE) is applied. Potential wander between the transmitter and the receiver clocks is compensated in the adaptive equalizer. After equalization, signal is decimated to 1 Sps to evaluate signal performance metrics: bit error ratio (BER) and normalized generalized mutual information (NGMI). For PAM-3/6, this evaluation is performed from two-dimensional constellations (c.f., Figs. 1(g,h)) spanned by odd and even PAM timeslots. This decoding requires prior synchronization, which is performed by inspecting the constellation for the absence of a forbidden symbol (center symbol in 3×3 constellation grid, or corner symbols in 6×6 grid).

Polybinary signals ($H$=1 bit/sym in all cases) are obtained by digitally convolving a binary signal with a polybinary filter having an impulse response $(1+z^{-1})^n$, where $n\in\{1,2,3\}$, corresponding to, respectively, duobinary, tribinary, and tetrabinary. In time domain, the polybinary filter causes controlled intersymbol interference spanning precisely $n$+1 symbols, while in frequency domain it is equivalent to a multiplication of the signal power spectrum by

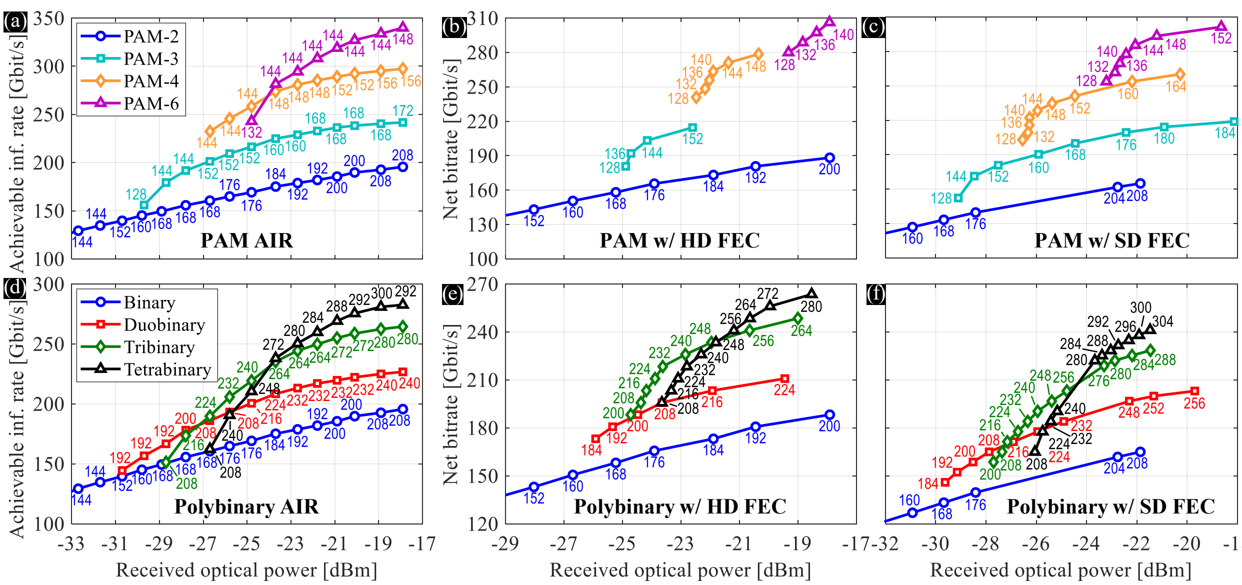


Fig. 2. Results for PAM (a-c) and polybinary (d-f). AIR (a,d). Net bitrates: assuming HD FEC (b,e) and SD FEC (c,f).

$|\cos(\pi f / R_s)|^{2n}$, with $f$ being the frequency and $R_s$ symbol rate. Thus, larger fraction of signal power concentrates at lower frequencies as polybinary filter order increases. Such encoded signal is then resampled to 256 GS/s. The receiver DSP for polybinary is similar to the one applied for PAM. Equalizer at the receiver uses a multi-level signal after $(1+z^{-1})^n$ polybinary filtering as a reference. A low-complexity Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm with a small number of states equal to $2^n$ is then used to decode the polybinary signal back to the binary sequence. Log-likelihood ratios (LLRs) obtained from BCJR are subsequently used for computation of the NGMI metric. Bit decisions are made based on the LLR sign, thus BER can also be computed.

## 3. Performance evaluation and discussion

For each combination of modulation format and symbol rate, the received optical power (ROP) is swept. At a constant ROP, NGMI obtained using a specific modulation format decreases as $R_s$ increases. The achievable information rate (AIR) is computed as $AIR{=}NGMI{\cdot}H{\cdot}R_s$, which represents a theoretical upper bound on the information rate which could be reached with an ideal bit-metric decoding. In Figs. 2(a,d), only the highest AIR at each ROP is shown for the investigated modulation formats, with $R_s$ indicated next to each point, at which the reported value is found. As shown in Figs. 2(a,d), at ROP of −17.9 dBm, AIRs of 340 Gbit/s and 283 Gbit/s are achieved by 148 GBd PAM-6 and 292 GBd tetrabinary modulations. As the ROP decreases, the performance degrades faster for PAM-6 and tetrabinary signals compared to PAM and polybinary signals of a lower order, which become better choices below certain ROPs. However, at nearly all indicated ROPs, a higher AIR can be observed in Fig. 2(a), as opposed to Fig. 2(d), demonstrating the advantage of PAM to support high-speed optical lanes. The achieved net bitrates are plotted in Figs. 2(b,c,e,f) under pragmatic HD (b,e) and SD (c,f) FEC codes. For HD FEC, net bitrate curves are approximated by interpolation of the measured BER vs ROP curves at the FEC binary symmetric channel (BSC) BER threshold value of the specific code, while for SD FEC by interpolation of the measured NGMI vs ROP curves at the FEC NGMI threshold value of the code. After interpolation, the net bitrate, $R_b$, is computed as $R_b{=}R_c{\cdot}H{\cdot}R_s$, where $R_c$ is the code rate of the specific code under consideration, and plotted against ROP. The HD FEC assumes a staircase code with $R_c{\approx}0.9412$ (BER threshold of $4.7{\times}10^{-3}$), except for PAM-6 which assumes a staircase code with $R_c{\approx}0.8750$ (BER $1.03{\times}10^{-2}$). These codes target post-FEC BER<$10^{-15}$ [11]. The soft-decision FEC assumes a concatenated code composed of: an inner spatially-coupled low-density parity check (SC-LDPC) code with $R_c$=0.8 at NGMI=0.845, leading to a post-inner-FEC BER <$10^{-5}$; an outer Bose-Chaudhuri-Hocquenghem (BCH) HD FEC code at $R_c$=0.9915 targeting post-outer-FEC BER <$10^{-15}$; overall $R_c$=0.7932. Similar to AIR observation, PAM in Figs. 2(b,c) leads to generally better results compared to polybinary modulation in Figs. 2(e,f) regardless of FEC type. The highest net bitrate assuming HD FEC exceeds 306 Gbit/s and is obtained with a 140 GBd PAM-6 signal at −17.9 dBm ROP, while 301 Gbit/s can be reached with 152 GBd PAM-6 at −18.6 dBm assuming SD-FEC. For polybinary, the highest net bitrate of 264 Gbit/s is observed with 280 GBd tetrabinary at −18.5 dBm when assuming HD FEC.

## 4. Conclusion

We have experimentally evaluated PAM and polybinary modulations as candidates to realize optical lanes for next-generation intra-DCIs. We tested PAM-2, -3, -4, -6, as well as duo-, tri- and tetrabinary modulations in terms of achievable information rate (AIR) and net bitrate when employing HD or SD FEC. We showed that while both signaling schemes can be used to increase information rate beyond conventional binary modulation under limited system bandwidth, conventional PAM can ultimately provide higher AIR and deliver higher net bitrates at better sensitivities.
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