50GBaud PAM-4 IM-DD Transmission with 24% Bandwidth Compression Based on Polybinary Spectral Shaping

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Abstract *We experimentally and numerically investigate the minimum electrical bandwidth for 50GBaud PAM4 detection with polybinary spectral shaping. With only 19GHz electrical brick-wall bandwidth, 100Gb/s PAM-4 transmission is demonstrated with 24% bandwidth compression at BTB and 1km SSMF scenarios.*

Introduction

To satisfy the requirement for high-capacity optical data transmission due to the rapid development of Internet of Things, artificial intelligence application, and other broadband services, there are extensive studies on intensity modulation direct-detection (IM-DD) system thanks to its lower cost compared with coherent detection system. The IM-DD system based on 4-level pulse amplitude modulation (PAM-4) format is one of promising candidates to realize low cost and power consumption with practical computational complexity, compared with discrete multi-tone modulation and multiband carrier-less amplitude and phase modulation. Recently, the IEEE 400GbE P802.3bs task force has adopted PAM-4 for 400GE Ethernet interface[1].

In theory[2], 25GHz bandwidth is required for 50Gbaud PAM-4 transmission without inter-symbol interference (ISI). However, due to the limited bandwidth of commercial devices, the low-pass filtering-induced ISI needs to be compensated by advanced digital signal processing (DSP) techniques, offering cost-effective solutions with 20G-class transceivers.

For DSP enabled schemes to reduce hardware cost, Faster-than-Nyquist (FTN) techniques can be used to reduce signal bandwidth and improve SE considerably, but inducing ISI. In the recently reported FTN PAM-4 transmission, a single-Lane 145 Gb/s IM-DD transmission was demonstrated using a combination of Tomlinson-Harashima precoding (THP) to mitigate the ISI and Volterra nonlinear equalizer (VNLE) with 4th-order kernels to mitigate the nonlinear distortions with a 33GHz bandwidth limited transmitter[3]. 94Gbaud FTN PAM-4 was achieved using a joint of THP and a non-linear equalizer with an 80GSa/s DAC after 2 km of standard single-mode fiber (SSMF) at 1550 nm[4], which reached a FTN rate ($\frac{Nyquist\ bandwidth}{system\ bandwidth}-1$) of 42.4%. However, the filter coefficients of the transmitter THP need to be measured to reduce precoding loss using a decision feedback equalizer (DFE) at the receiver operating at error-free propagation mode[5], which is complicated and not suitable for time-variant channel. Compared with THP, a straightforward precoding technique can be applied to narrow signal bandwidth by introducing a controlled ISI, known as duobinary precoding or partial response. The controlled ISI is eliminated by maximum likelihood sequence estimation (MLSE) at the receiver. Single-lane 180Gb/s duo-binary PAM-4 (DB-PAM-4) transmission was demonstrated over 2km SMF and it proved that DB-PAM-4 outperforms conventional PAM-4 in bandwidth-limited system[6]. 100 Gb/s DB-PAM-4 transmission was demonstrated over 50 km SSMF in the O-band using a 20GHz silicon-based transmitter and a 25GHz PIN+TIA-based receiver[7]. Up to 205GBaud OOK signal was achieved with a 120GSa/s DAC based on high-order partial response narrowing[8], which shown improved tolerance against bandwidth limitation of polybinary precoding than 1st-order DB.

In this paper, we investigate the minimum electrical bandwidth for 50GBaud FTN PAM-4 transmission by polybinary precoding. The bandwidth limitation is applied with digital brick-wall filter. A bandwidth compression ratio ($\frac{practical\ bandwidth}{Nyquist\ bandwidth}$) of 0.76, or equivalently FTN rate of 31.6%, is realized with a 64GSa/s DAC and only 19GHz digital brick-wall filter at BTB and 1km SSMF transmission. After 1km SSMF transmission with direct detection, the bit error rate (BER) achieves the 20% hard-decision forward error correction (HD-FEC) threshold of 1.5×10^{-2}. Electrical bandwidth from 25GHz to 18GHz with different duobinary orders are also evaluated.

Simulation and experimental setup

Fig.1 shows the simulation and experimental setup of FTN PAM-4 transmission system. At the transmitter DSP, the PAM-4 sequence convolves with 1-order DB filter with coefficients of [1 1], 2-

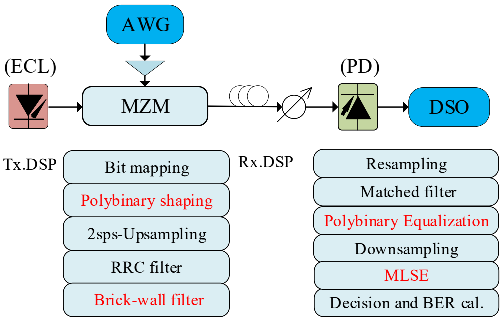


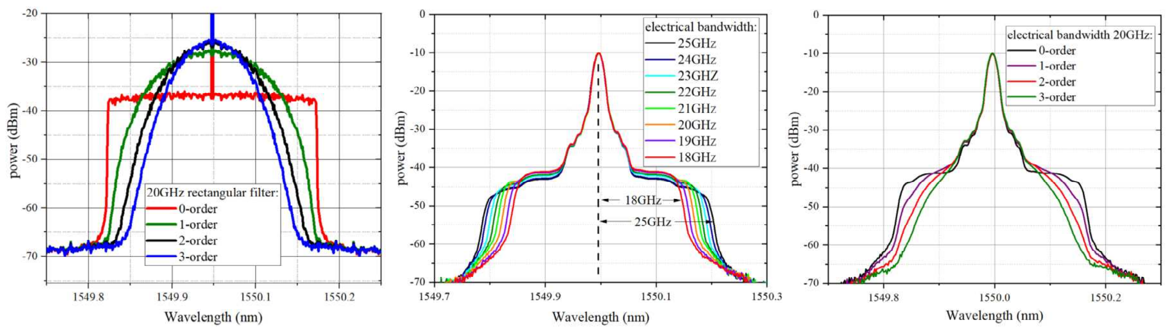
Fig. 1: Simulation and experimental setup.

order DB filter [1 2 1], or 3-order DB filter [1 3 3 1] at 1 sample per symbol (SPS), respectively. The precoded polybinary PAM-4 sequence is upsampled to 2 SPS and shaped by a root raised cosine (RRC) filter with roll-off factor of 0.01. Then digital brick-wall filter is used to cut off the high frequency components to lower signal bandwidth and realize FTN transmission. The 50Gbaud PAM-4 electrical signal after polybinary precoding and digital brick-wall filter is generated by an arbitrary waveform generator (Keysight M8195A) of 25 GHz 3-dB bandwidth, operating at 64GSa/s and then loaded into Mach Zehnder modulator (MZM, Fujistu) of 25GHz 3dB bandwidth biased at quadrature point after amplified by an electrical amplifier (SHF 408M 65GHz). After 1km SSMF transmission, the received optical power is attenuated to 2dBm by a variable optical attenuator at the receiver. The optical signal is then detected by a 40GHz bandwidth linear PD (Picometrix PT-40A). Finally, the waveform is captured by a real-time digital storage oscilloscope (Tektronix DPO75902SX) operating at 100GSa/s for offline DSP. At the receiver DSP, the detected waveform is firstly resampled to 2SPS and shaped by a RRC matched filter with a roll-off factor of 0.01. After synchronization, the sequences are fed into the sparse Volterra equalizer. The equalizer taps are optimized to 101,11,5 for low computational complexity. The filter taps are updated by the recursive least square (RLS) algorithm based on training sequence with polybinary precoding. Then, Viterbi decoding algorithm based MLSE is applied to remove the introduced ISI to recover the PAM-4 signal. After de-mapping, the BER is calculated by a collecting of ~6.5×10^5 bits.

Results and Discussions

Fig. 2(a) depicts the simulated optical spectra of 50Gbaud PAM-4 signal with 0-order, 1-order, 2-order, 3-order polybinary. It shows that, as the order of polybinary increases, the low-frequency components become larger and high frequency region falls faster and the 3-dB bandwidth of signal becomes narrower. Fig.2(b) shows the measured spectra of different bandwidth digital brick-wall, ranging from 25GHz to 18GHz at 0.02nm resolution. With the bandwidth of digital brick-wall filter becoming smaller, the optical sprectra become narrower because the high-frequency compoents are filtered out. Fig.2(c) compares the measured spectra of 50GBaud PAM-4 signal with different polybinary orders. The dark optical spectrum corresponds to Nyquist shaping with a 0.01 roll-off factor as a reference. We can find that the signal energy is concentrated in the low frequency region, which is consistent with Fig.2(a).

Fig. 3(a) shows the simulated BERs versus different electrial bandwidth of a rectangular filter. We keep OSNR of simulation the same as experiment in order to explore the FTN limitaion of 50GBaud PAM-4 signal. It can be observed that system performance degrades with the electrical bandwidth decreasing and the BERs for 3-order duobinary shaping are stable at 1.2×10^{-2}, because the signal energy is concentrated in the low frequency region, and the reduction of the electrical bandwidth has little impact on it. The BER of 1.2×10^{-2} is achieved below the 20% HD-FEC threshold with 18GHz electrical bandwidth and 2-order duobinary shaping. Fig.3(b) depicts the measured BERs versus different electrical bandwidth in the above experimental setup at



(a) (b) (c)

Fig. 2: (a) The simulated optical spectra of different duobinary precoding orders in 20GHz rectangular filter. The measured optical spectra of (b) different electrical bandwidth and (c) different duobinary precoding orders with 20GHz digital brick-wall filter.

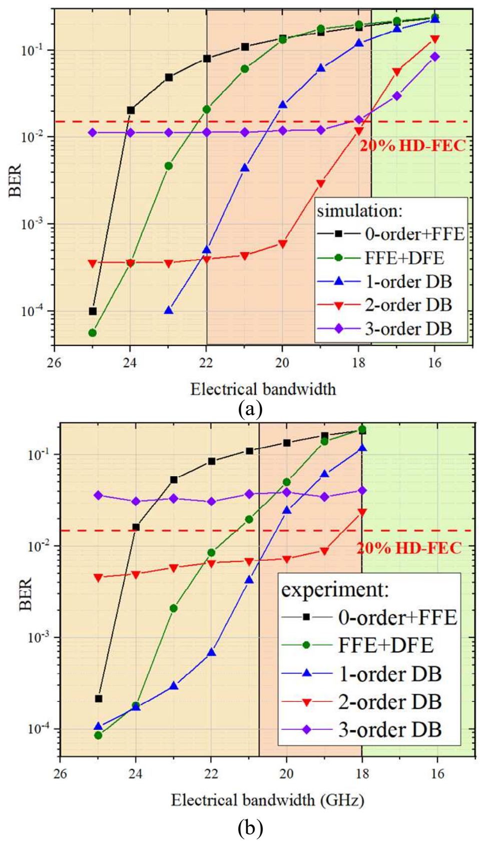


Fig. 3: The BERs versus electrical bandwidth with different duobinary orders in the (a) simulation and (b) experiment at BTB scenario.

BTB. It is worth noting the system BER performance deteriorates by two orders of magnitude sharply as the electrical bandwidth dreacreases from 25GHz to 24GHz in both experiments and simulations. When the system is bandwidth limited slightly (25GHz-21GHz), 1-order duobinary shaping outperforms than other orders. 2-order duobinary shaping shows the best performance when it is bandwidth limited severely (21GHz-18GHz). Since the signal energy is squeezed into 18GHz, the BERs of 3-order shaping signals fluctuate slightly around 3×10^{-2} in the tested electrical banwidth. The results are almost consistent with simulation. 3-order duobinary shaping signal deteriorates from 17GHz bandwidth, as shown in the Fig.3(a). However, the BER below 17GHz electrial bandwith is above the 20% HD-FEC threshold. It should be noted that the ideal brick-wall bandwidth limitation is investigated in this work, which can be regarded as a lower bound of practical situation.

Fig. 4 plots the measured BERs versus electrical bandwidth at BTB scenario, and after 1km SSMF transmission, respectively. The polybinary order is optimized for each brick-all bandiwdth and it is 1-order for 25GHz to 22GHz,

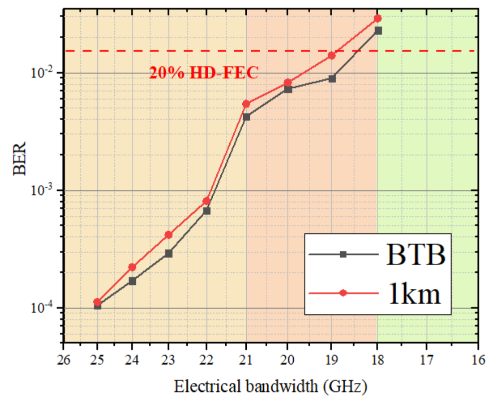


Fig. 4: Measured BERs versus electrical bandwidth at BTB scenario, and after 1km SSMF transmission, respectively.

2-order for 21GHz to 18GHz. Thanks to the 2-order duobinary shaping and MLSE, the BERs under 19GHz electrical bandwidth at BTB and 1km SSMF transmission scenerios are 9×10^{-3} and 1.4×10^{-2}, which is below 20% HD-FEC threshold.

Conclusions

We investigate the minimum transmission bandwidth of 100Gb/s FTN PAM-4 in IM-DD system. Both numerical and experimental results show that high-order DB can greatly improve the bandwidth limitation tolerance at the cost of higher BER floor due to the increased eye levels. 100Gb/s PAM-4 transmission with only 19G electrical bandwidth is demonstrated by polybinary spectrum narrowing and MLSE at both BTB and 1km SSMF scenario, which equals to a bandwidth compression ratio of 0.76. The results indict that the feasibility to combine low-bandwidth devices and advanced DSP techniques to lower the cost for 100Gb/s high-speed optical interconnects.

Acknowledgements

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References

[1] IEEE802.3,Dec.2017.[Online].Available:http://www.ieee802.org/3/bs/index.html

[2] Haykin, Simon S. Digital communications. New York: Wiley, 1988.

[3] M. Xiang, et al., “Single-Lane 145 Gbit/s IM/DD Transmission With Faster-Than-Nyquist PAM4 Signaling,” IEEE Photon. Technol. Lett., 30(13), 1238-1241 (2018).

[4] Q. Hu, et al., “Up to 94 GBd THP PAM-4 Transmission with 33 GHz Bandwidth Limitation,” 2018 European Conference on Optical Communication (ECOC), 2018, pp. 1-3.

[5] S. An, et al., "FTN SSB 16-QAM Signal Transmission

and Direct Detection using a THP-MIMO-FFE," in Optical Fiber Communication Conference (OFC) 2020, paper M3J.4.

[6] Q. Zhang, et at., "Single-lane 180 Gbit/s PAM-4 signal transmission over 2 km SSMF for short-reach applications," Opt. Lett. 41, 4449-4452 (2016).

[7] M. Ghulam Saber, et al., "100 Gb/s/λ Duo-Binary PAM-4 Transmission Using 25G Components Achieving 50 km Reach," in IEEE Photonics Technology Letters, vol. 32, no. 3, pp. 138-141.

[8] Y. Zhu, et al., "Sub-Sampling Generation and Transmission of 205Gbaud OOK Signal with 120GSa/s DAC Based on High-Order Partial Response Narrowing, " in Asia Communications and Photonics Conference (2020), paper M4D.4.