Combined Probabilistic Shaping and Nyquist Pulse Shaping for PAM8 Signal Transmission in WDM Systems

Xiao Han[1,2*], Mingwei Yang[1], Ivan B. Djordjevic[1], Yang Yue[2], Qiang Wang[2], Zhen Qu[2], Jon Anderson[2]
[1]*ECE Dept., University of Arizona, 1230 E Speedway Blvd, Tucson, AZ*
[2]*Juniper Networks, 1133 Innovation Way, Sunnyvale, CA*
[*]*xhan322@email.arizona.edu*

Abstract: We use the LDPC-coded probabilistically shaped PAM8 signaling combined with Nyquist pulse shaping to improve the transmission performance in a WDM system. We find that the combination of these shaping schemes offers great performance improvement.
OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (060.4230) Multiplexing

1. Introduction

Pulse amplitude modulation (PAM) is widely used in inter-data center communication, thanks to its simplicity, low cost, high reliability, and low power consumption. The widely used uniform distributed PAM modulation has a large gap to the Shannon limit. To reduce this gap, researchers consider applying the probabilistic shaping scheme together with FEC coding [1].

Wavelength-division multiplexing (WDM) has been overwhelmingly used in modern optical transmission systems. However, given the fixed wavelength spacing each wavelength channel represents a band-limited channel, and high baud rate signal transmission will cause intersymbol interference (ISI) in the presence of residual chromatic dispersion. To make the transmitted signal more suitable for the fiber-optics communication channel and improve the spectral efficiency, an efficient approach is to apply the Nyquist pulse shaping (NPS) scheme [2,3].

In this paper, we numerically and experimentally investigate the transmission performance of low-density parity-check (LDPC) coded probabilistic shaped PAM8 combined with NPS in WDM system. We find that combining probabilistic shaping (PS) and Nyquist shaping in PAM8-WDM system significantly improves the overall BER performance. This scheme is suitable for short reach applications, such as data centers and passive optical networks.

2. System description

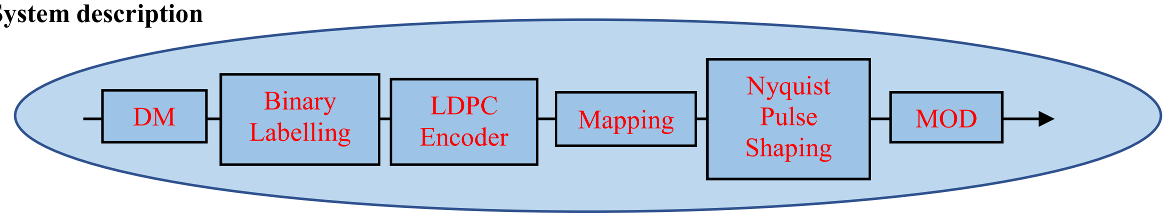


Fig.1 The PS-NPS-PAM8 signal transmitted in each wavelength channel. DM: distribution matcher, MOD: electro-optical modulator.

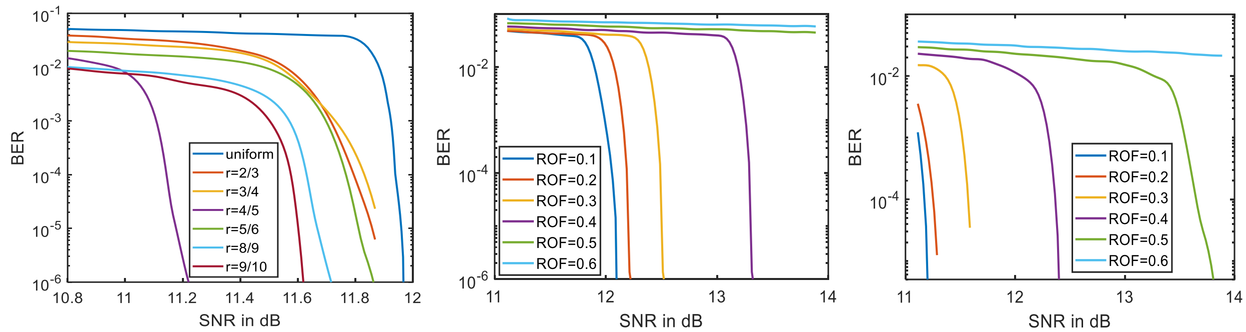
Figure 1 shows the generation configuration of PS-NPS-PAM-8 signal. After the PAM8 mapping, we employ a super Gaussian filter centered at each carrier wavelength to select the desired signal in every single wavelength channel. In PS-PAM-8 format modulation, we use the exponential distribution, which is introduced in [1]. In WDM systems, we use the square-root raised cosine (SRRC) filter [2], whose transfer function is given by $H_{SRRC}(\omega) = \sqrt{H_{RC}(\omega)}$, wherein

$$H_{RC}(\omega) = \begin{cases} T_S & 0 \le |\omega| < \pi(1-ROF)/T_S \\ \frac{T_S}{2}\left(1 - \sin\left[\frac{T_S}{2 \times ROF}\left(|\omega| - \frac{\pi}{T_S}\right)\right]\right), & \pi(1-ROF)/T_S \le |\omega| < \pi(1+ROF)/T_S \\ 0 & |\omega| > \pi(1+ROF)/T_S \end{cases}$$

with ROF being the roll-off factor (ROF) and T_S symbol duration.

3. Simulation Results

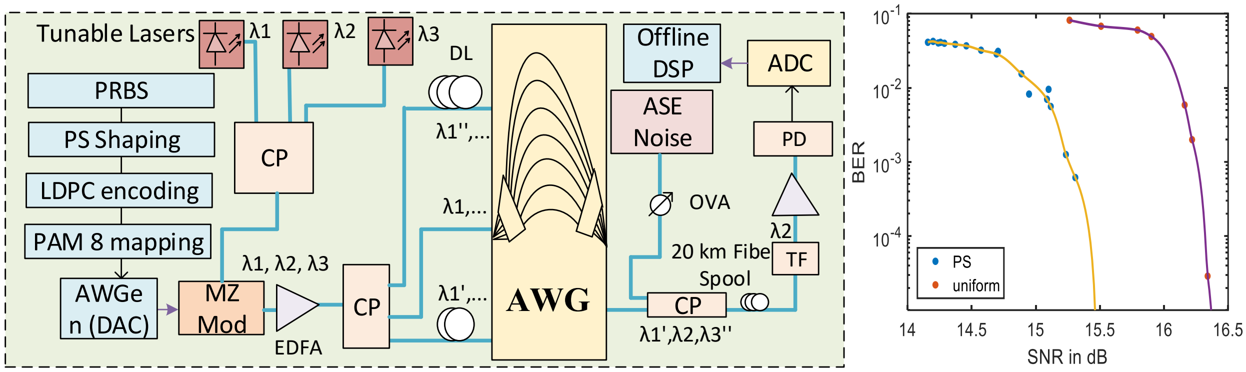
Figure 2 (a) shows the comparison of BER performance of PS distribution and uniform distribution for PAM-8 signals. To make the comparison fair, we need to make sure that each modulation scheme has the same achievable information rate (AIR), in this paper, the target AIR is set to 1.875 bits/symbol for all code rates. From this figure we can conclude that all PS distributions outperform the uniform distribution, and among them the one with code rate equal to 0.8 has the best improvement in BER performance, which offers 0.8 dB SNR gain over uniform distribution at BER of 10^{-5}. Figure 2 (b-c) shows the BER performance for different values of ROF, for both LDPC-coded uniform distribution and PS distribution. We can see that a smaller value of ROF can lead to the frequency response of a rectangular shape, improving the spectral efficiency, and simultaneously improving the BER performance for the same SNR.



(a) (b) (c)

Fig. 2 (a) BER performance for different LDPC code rates (r). BER performance for different ROF values for the same achievable information rate of 1.875 bits/symbol for: (b) PS distribution with LDPC code of rate r=0.8 and (c) uniform distribution with LDPC code of rate r=0.625.

4. Experimental setup and results



(a) (b)

Fig. 3(a) Experimental data center setup. CP: coupler, DL: delay line, TF: tunable filter, OVA: optical variable attenuator. (b) BER performance comparison between LDPC-coded PS and uniform distributions.

We experimentally verified the performance of PS PAM-8 transmission in DWDM system with the testbed depicted in Fig. 3(a). Three 10 kHz-linewidth, continuous-wave, tunable sources (with the following center frequencies f_1=193.30 THz, f_2=193.35 THz, and f_3=193.40 THz) are combined with an optical coupler and applied to a Mach-Zehnder modulator. The binary data sequence is PS shaped and encoded with an LDPC code (code rate: 0.8, and codeword length: 16935). The encoded bits are mapped to eight levels symbols and are pulse shaped by an arbitrary waveform generators (AWGen) to create 25 GBaud PAM-8 signals. The resulting signals are boosted by an erbium-doped fiber amplifier (EDFA) with a 6 dB noise figure. The boosted signal is split and interleaved into three different length fibers and such signals are applied to a 32×32 arrayed waveguide grating (AWG)-based datacenter network. ASE noise is inserted and mixed with the output 50GHz grid DWDM signal by a 2×2 coupler. Optical variable attenuator (OVA) is employed after ASE noise source to emulate the different optical SNR (OSNR) channel conditions. The targeted wavelength λ_2 is selected by a tunable filter and such signal is detected by a p.i.n. photodetector (PD). Further, an analog-to-digital convertor (ADC), operating at 50 Gbaud sampling rate, is employed to collect the received baseband signal. The collected points are stored locally for offline digital signal processing.

Figure 3(b) shows the BER performance of LDPC-coded PS and uniform distributions for PAM8. Clearly, LDPC-coded PS distribution outperforms LDPC-coded uniform distribution by 1.1 dB at BER of 10^{-5}.

5. Conclusion

Based on simulation and experimental results, we conclude that the probabilistic shaped PAM-8 modulation represents an excellent candidate for the short distance data center communication. To satisfy the increasing requirements for high spectral efficiency and high baud rate, combining PS with Nyquist pulse shaping in WDM system provides a great improvement in the system BER performance.

References

[1] X. Han, I. B. Djordjevic, "Probabilistically shaped 8-PAM suitable for data centers communication," ICTON 2018, p. Th.B3.4 (2018).

[2] Y. Yang, et al., "Transmitter skew tolerance and spectral efficiency tradeoff in high baud-rate QAM optical communication systems," Optics Express **26** (12): 15045-15058 (2018).

[3] N. Kikuchi, R. Hirai, "Intensity-modulated / direct-detection (IM/DD) Nyquist pulse-amplitude modulation (PAM) signaling for 100-Gbit/s/λ optical short-reach transmission" ECOC 2014, p. 4.12 (2014).

[4] M. Yang, et al., "SDN-based application driven in-band adaptive coding in data centers," OFC 2018, p. W2A.21 (2018).