Experimental Comparison of PAM-8 Probabilistic Shaping with Different Gaussian Orders at 200 Gb/s Net Rate in IM/DD System with O-Band TOSA

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Abstract For 200Gb/s net rates, cap probabilistic shaped PAM-8 with different Gaussian orders are experimentally compared against PAM-8. In back-to-back and 5km measurements, cap shaped 85-GBd PAM-8 with Gaussian orders of 5 outperforms 71-GBd uniform PAM-8 by up to 2.90dB and 3.80dB in receiver sensitivity, respectively.

Introduction In the coming years, data center traffic is expected to grow exponentially due to the cloud services such as video-on-demand, cloud computing, gaming, and internet-of-things (IoT). To date for short reach (below 10 km), intensity modulation with direct detection (IM/DD) is preferred over coherent systems, due to the advantages like low power consumption, simpler transceiver design as well as smaller footprint [1]. For operating close to the Shannon limit and achieving finer granularity probabilistic shaping (PS) is vastly explored and even implemented in commercial coherent system-based products for long-haul transmission. Due to the availability of high bandwidth opto-electronic components [2,3] PS is also being explored for IM/DD based short reach applications [4-7]. In our recent publications, with cap-shaped PS with Gaussian order of 2, in term of receiver sensitivity, we show a performance improvement of up to 1 dB [4] and 3.5 dB [5] in C and O-band, respectively. Furthermore, with a combination of PS and geometric shaping (GS) up to 1.1 dB performance gain has been reported [6].

This work is a follow-up on our previous paper [5], where we have demonstrated that 2nd order Gaussian shaped Maxwell Boltzmann (MB) distributed cap-shaped PS outperforms cup-shaped PS in the considered scenarios. In this work, we evaluate MB distributions with different Gaussian orders [8] (Fig. 1) for cap-shaped PS only. The implementation technique is described in the next section. We compare experimentally this scheme with uniform 8-level pulse amplitude modulation (PAM). The experimental setup is based on a transmitter optical subassembly (TOSA), which is next generation feasible component on the transmitter side. The experimental results indicate that for PS PAM-8, higher-order Gaussian MB distributions outperform signalling without shaping or lower-order MB distributions. Furthermore, with 7% hard decision (HD) forward error correction (FEC) with bit error rate (BER) threshold of 3.8×10⁻³, 85 Gbd cap-shaped PAM-8 with an entropy (H) of 2.5492 bit/symbol improves the receiver sensitivity by up to 3.80 dB for the case of 5 km transmission compared to 71 Gbd uniform PAM-8.

Cap PS With Different Gaussian Orders

The spectral efficiency of a transmission system with probabilistic amplitude shaping (PAS) [9] is given by

\[ SE = \sum_{i} P_i \log_2 \left( \frac{1}{P_i} \right) \]

(1)

where \( P_i \) is the input distribution \( H(P_i) \) the entropy in bits, \( m \) the number of bit-levels, i.e., \( m = 3 \) for PAM-8, and where \( R_{FEC} \) is the FEC rate. The PS overhead in bits is \( m - H(P_X) \). For fixed net bit rate and FEC overhead, the PS overhead is a function of the baudrate. Most commonly, the MB distribution

\[ P_{MB}(x) \propto \exp \left( -\frac{x^2}{\nu^2} \right) \]

(2)

is chosen, as it minimizes average power. The parameter \( \nu \) is chosen according to the desired overhead. Consequently, for each PS overhead,
Experimental Setup and DSP

The experimental setup is represented in Fig. 2. Below each electro-optical component, its 3-dB bandwidth (BW) is indicated. The offline transceiver digital signal processing (DSP) is also depicted as a sequence of steps. A pseudorandom binary sequence (PRBS) was generated and mapped to a PAM-8 levels’ array. Similarly for PS PAM-8, random symbols were drawn from a cap MB distribution with desired entropy. Considering 7% HD-FEC, targeting 200 Gbit/s net bit rate, a symbol rate of 71 GBd was used to compensate for nonlinearities introduced by AWG, EML, SOA, EA, and square-law detection. Afterward, symbol decision was performed on the PAM-8 symbols. The symbol
decision thresholds were optimized based on the distribution probabilities of each level. Afterward, the symbols were de-mapped to bits and the BER was calculated.

Transmission Results and Discussions

The experimental results are presented in Fig. 3 in terms of pre FEC BER variation over ROP. Results measured for B2B and 5 km transmission and are shown in Fig. 3(a) and (b), respectively. As a performance threshold criterion, 7% HD-FEC is considered. A solid line with circle markers represents uniform 71 Gbd uniform PAM-8. The dashed lines with square markers represent cap-shaped 80 Gbd PAM-8, and dotted lines with diamond markers indicate cap-shaped 85 Gbd PAM-8 with Gaussian order of 2, 3.5 and 5, respectively. Similarly, dashed-dotted lines with pentagon markers represent cap-shaped 90 Gbd PAM-8.

Evaluating the results in terms of receiver power sensitivity, uniform PAM-8 has reached the HD-FEC threshold at -6.84 dBm. On the other hand, cap-shaped PAM-8 80 Gbd with Gaussian order 2 and 3.5 reaches the HD-FEC threshold at -8.3 dBm, while with Gaussian order 5, the performance is improved by up to 0.6 dB. The performance with cap-shaped 85-Gbd PAM-8, with Gaussian order 3.5 performs almost similar to the cap-shaped 80 Gbd PAM-8 with Gaussian order 5. Furthermore, cap-shaped 85 Gbd PAM-8 with 2.5492 bit/symbol with Gaussian order of 5 performs 0.8 dB better compared to the cap-shaped 80 Gbd PAM-8 with 2.6963 bit/symbol with Gaussian order 5, and approximately 2.9 dB better compared to the 71 Gbd uniform PAM-8. The comparison is particularly interesting for cap-shaped PAM-8 90 Gbd with 2.3867 bit/symbol for different Gaussian orders. For instance, for the Gaussian order of 2, the performance is very similar (only slightly worse) compared to cap shaped PAM-8 80 Gbd with Gaussian order of 2, since the overall channel BW becomes critical and a comparatively high number of symbols on the outer levels makes the overall performance degradation. As expected, the performance and is improved by up to 0.8 and 1 dB with Gaussian order 3.5 and 5, respectively, as the outer symbols become less probable.

For 5 km transmission case, uniform PAM-8 shows ≈ 0.6 dB penalty compared to B2B case, while transmission with PS PAM-8 shows negative penalty (about -0.3 dB) with Gaussian order 5. This also indicates that accumulated dispersion is much more severe and contributes to the inter-symbol interference (ISI) on uniform symbol distribution compared to the fewer symbols on the outer levels.

Conclusion

We have shown an experimental comparison between uniform PAM-8 with cap-shaped Maxwell-Boltzmann distributed PAM-8 with different symbol rates and Gaussian order of 2, 3.5, and 5 for each symbol rate. A net bit rate of 200 Gb/s was targeted and adequate overhead for a 7% HD-FEC was allocated. While comparing uniform PAM-8 and PS PAM-8, PS PAM-8 85 Gbd with Gaussian order of 5 performs the best and outperforms uniform PAM-8 by around 2.9 dB. For 5 km transmission, the power sensitivity performance is improved up to 0.9 dB over B2B scenario.

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