Demonstration of shallow probabilistic shaping for low-power transmissions at 400 Gb/s and beyond

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Abstract: We demonstrated experimentally probabilistic shaping (PS) with a 5% increase in symbol rate for 400 Gb/s 16-ary quadrature amplitude modulation. Such a shallow PS enables significant improvement of the theoretical performance with limited incremental power consumption, peak-to-average power ratio (PAPR), and kurtosis. The PS signal was transmitted over a typical terrestrial link at a 0.8 dB larger Q margin than with uniform signaling. There were no excessive penalties such as transceiver and fiber nonlinearities because of the limited PAPR and kurtosis. Throughout an 8-hour nonlinear transmission test, there was no significant performance variation, and no residual errors after forward error correction decoding.

Keywords: distribution matching, fiber nonlinearity, forward error correction, probabilistic shaping, quadrature amplitude modulation

Classification: Fiber-Optic Transmission for Communications

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1 Introduction

Optical fiber communication systems are required to carry a large amount of data at a high energy efficiency. Following on from the deployment of coherent detection with digital signal processing (DSP) [1], the coding and modulation techniques
have evolved significantly and have contributed to advancements in optical fiber communications [2]. The latest solution for the 400 Gb/s standard is polarization division multiplexed (PDM) 16-ary quadrature amplitude modulation (QAM) with bitwise reception and soft-decision (SD) forward error correction (FEC) [3, 4]. Furthermore, an alternative to pragmatic uniform signaling, reverse concatenation probabilistic shaping (PS), namely probabilistic amplitude shaping (PAS), is arousing wide interest because of its capacity-approaching performance, rate adaptability, and low complexity. It places the distribution matching (DM) for the PS outside the FEC coding, which enables significantly easier implementation of PS than previously [5, 6].

On the other hand, there are still several practical drawbacks to PS [7]. The first is increased throughput at the FEC coding stage due to the redundancy added for the PS. The second is increased peak-to-average power ratio (PAPR) due to the centralized probability mass function, leading to a large modulation loss and a reduced transceiver signal-to-noise ratio (SNR) [8] resulting from their combination with limited digital resolution, the effective number of bits, and device nonlinearity. As well as PAPR, the kurtosis of PS signals can be larger than for uniform signals, which brings with it increased degradation due to fiber nonlinearity [9, 10]. Considering such practical limitations, shallow PS with granular base constellations is more advantageous than deep PS with a fixed base constellation.

Thus in this work, we demonstrated experimentally shallow PS at 400 Gb/s system throughput. A PS with a 5% symbol rate increase achieves a 0.8 dB larger Q margin at the expense of a marginal increase in power consumption, but without excessive practical penalties.

2 Shallow probabilistic shaping

While the power consumption of FEC has been studied thoroughly, that for PS or DM has rarely been discussed. PAS usually combines PS with bit-interleaved coded modulation (BICM) [11]. In this case, PS can significantly increase the FEC throughput and power consumption, e.g., by 1.5 times, when we replace uniform 16-QAM with PS-64-QAM at a given system throughput, symbol rate, and code rate. If the base constellation is 256-QAM, the throughput and power increases can double. This drawback can be critical in the design of application specific integrated circuits (ASIC).

Note that the power consumption with DM is also crucial for low-power optical transmission. In fact, the implementation of DM remains a challenging issue when seeking high performance with limited power consumption. Only two DM techniques, hierarchical DM [12] and prefix-free code DM [13], have been reported with results from implementation in a field programmable gate array (FPGA) [14, 15]. Only hierarchical DM has been experimentally verified in real-time tests [12]. Hierarchical DM yields a low power consumption because it does not require high precision computation, but instead employs tree-structured look-up tables (LUTs) using random access memory (RAM) [12]. The power consumption of a small amount of RAM does not affect an ASIC-based implementation. For this reason we employed hierarchical DM for this work.
As introduced in Sec. 1, the practical performance problems arising from the larger PAPR and kurtosis of PS are non-negligible. Fig. 1 shows the signal statistics for (a) constellation gain $G = (2^\beta - 1)d_{\text{min}}^2/6P$ [11], (b) PAPR at 1 sample/symbol, and (c) excess kurtosis $\mathbb{E}[|X|^4]/\mathbb{E}^2[|X|^2] - 2$ [16] for Maxwell-Boltzmann distributed PS-256, 128, 64, 32, and 16-QAMs. The parameters $\beta$, $d_{\text{min}}$, $P$, $X$, and $\mathbb{E}[\cdot]$ represent the spectral efficiency, the minimum Euclidean distance, the average power of a two-dimensional symbol, the random variable of a two-dimensional symbol, and the expectation, respectively. The value of $\beta$ is equal to $\mathbb{H}(X) - R_{\text{loss,2d}}$, where $\mathbb{H}(\cdot)$ and $R_{\text{loss,2d}}$ denote the entropy and two-dimensional rate loss in DM. A deep PS (high redundancy PS) with a large base constellation is expected to cause practical performance degradation due to the large PAPR and excess kurtosis. Each red dot in Fig. 1 shows the operating point of the demonstration reported in this work (see Sec. 3), which is for 16-QAM based shallow PS. The value of $\beta$ is 3.84 bits per channel use, and the constellation gain is 0.65 dB (0.16 dB away from the theoretical limit for PS-16-QAM). This shallow PS closely approaches the Shannon capacity. The PAPR and excess kurtosis are respectively 3.7 dB and $-0.50$, their increases over uniform 16-QAM (PAPR of 2.55 dB and excess kurtosis of $-0.68$) are less than for ones based on higher-order constellations.

![Fig. 1. Signal statistics of (a) constellation gain, (b) PAPR, and (c) excess kurtosis as a function of spectral efficiency in Maxwell-Boltzmann distributed PS-QAMs.](image)

3 Experiments

We examined the transmission performance of 400 Gb/s PDM 16-QAM with and without shallow PS (which increases the symbol rate by only 5%). Fig. 2 shows the experimental setup for emulating a typical terrestrial wavelength division multiplexed (WDM) system. At the transmitter, the test signal with a center wavelength of 1590.41 nm was generated in an optical transceiver. The DSP generates a uniform 16-QAM or PS-16-QAM signal with hierarchical DM, whose spectrum was shaped...
with a root raised cosine lowpass filter having a rolloff factor of 0.2. A continuous wave (CW) light from a micro-integrable tunable laser assembly (μITLA) was modulated by the electrical signal from the DSP in an InP-based high-bandwidth coherent driver modulator (HB-CDM). The modulation losses were 22.5 dB and 23.0 dB for uniform and PS-16-QAM, respectively. The difference in modulation loss was less than the expected 1.15 dB given by the theoretical difference in PAPR. For the neighboring signals ranging from 1587.88 nm to 1593.79 nm at 100 GHz spacing, CW lights were emitted from seven μITLAs, multiplexed in an arrayed waveguide grating (AWG), and modulated in a lithium niobate PDM in-phase and quadrature Mach-Zehnder modulator (LN-mod) with drive signals from the DSP applied via driver amplifiers. The test and neighboring signals were combined in an optical coupler (CPL).

The transmission line was six spans of 80 km standard single mode fiber (SSMF) with seven nodes. The average span loss and the chromatic dispersion at 1590.41 nm were respectively 17.8 dB and 19.3 ps/nm/km. Each node consisted of two Erbium-doped fiber amplifiers and two wavelength selective switches (WSS). The noise figure of the EDFAs was 6.3 dB, and the total transmission distance was 480 km. Fig. 2(a) shows the received optical spectrum for the WDM signal.

At the receiver, the WDM signal was fed to the optical transceiver after being passed through a variable optical attenuator (VOA) for optical power control. The WDM signal was then mixed with a local oscillator light in a high-bandwidth intradyne coherent receiver (HB-ICR) and the test signal was coherently detected. Inside the DSP, the electrical signal was equalized (Fig. 2(b) is the recovered constellation of PS-16-QAM in a back-to-back configuration), softly demapped, and decoded by SD-FEC. PS decoding was also performed for the PS-16-QAM. The bit-error ratio (BER) was estimated from the number of flipped bits in the FEC decoding process. The BER so obtained was converted to a Q-factor.

Fig. 3 shows the experimental results for Q margin over the FEC threshold. Fig. 3(a) depicts the variation with launched power, used to examine the effects of

![Fig. 2. Experimental setup. Insets are (a) received optical spectrum and (b) transmitted constellation of PS-16-QAM.](image-url)
fiber nonlinearity. Although the report in [17] shows that PS has poorer tolerance of nonlinearity than uniform signaling, we did not see a larger nonlinear penalty in this experiment, and in this work the optimum launched power was the same (around 4 dBm/channel) for the uniform and PS cases. This would be because of similar statistics between uniform and PS-16-QAM, i.e., each signal had similar PAPR and excess kurtosis at the transmitter, and dispersion uncompensated SSMF transmission rapidly made each distribution Gaussian-like. As a result, the PS-16-QAM shows a 0.8 dB greater Q margin compared with uniform 16-QAM. Note that the DSP for the PS-16-QAM consumes 5% more power than the uniform 16-QAM at the FEC threshold for error free operation.

Fig. 3(b) shows the long-term stability of the PS-16-QAM signal at 4 dBm/channel. The Q-factor was measured every two seconds over 8 hours. Throughout the measurement period, the Q-factor was stable (its standard deviation was only 0.03 dB), and no residual errors were observed after FEC and PS decoding.

Fig. 3. Transmission performance; (a) fiber nonlinearity tolerance of uniform and PS-16-QAM, and (b) long-term stability of PS-16-QAM at 4 dBm/channel.

4 Conclusions

We reviewed the advantages of shallow PS and demonstrated 480 km of nonlinear transmission at 400 Gb/s throughput with a 16-QAM base constellation. There were no excessive practical penalties from transceiver noise and fiber nonlinearity because of the limited PAPR and kurtosis. We demonstrated a 0.8 dB improvement in performance, no significant performance variations, and no residual bit errors after
FEC and PS decoding during an 8-hour measurement of nonlinear transmission at 4 dBm/channel. Shallow shaping with granular base constellation is in practice key to low power transmission at 400 Gb/s and beyond.

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