PCS-16QAM vs QPSK: What is the best choice for Next-Generation Long-Haul 400G?

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Abstract *We experimentally compare PCS-16QAM and QPSK for 400G transmission at 128 Gbaud. A realistic, full system implementation that accounts for penalties from the FEC, distribution matcher, transceiver impairments, fiber nonlinearity, and DSP, reveals that the theoretical 0.8 dB gain of PCS-16QAM is reduced to only 0.1 dB.*

Introduction

The use of probabilistic constellation shaping (PCS) has gained much popularity in recent years. PCS has typically been the choice for many of the recent record experimental demonstrations[1]–[4]. In addition, actual commercial transceivers are already exploiting the benefits of PCS modulation[5]. These include the capability to adapt the bitrate by simply adapting the entropy, providing fine granularity. In addition, PCS modulation provides 1.53 dB asymptotic SNR gain compared to conventional uniform modulation formats[6].

The SNR gain provided by PCS modulation is however reduced when operating at low signal-to-noise ratio (SNR). Compared to quadrature phase-shift keying (QPSK), PCS modulation only provides 0.8 dB theoretical gain when operating with typical forward error correction (FEC) overhead of about 20-25%; see Fig. 1 in which we present the normalized generalized mutual information (NGMI) curves for QPSK and PCS-16 quadrature amplitude modulation (QAM)[7]. Moreover, it is also well known that this gain is expected to be reduced when considering realistic system implementation, as well as transmission performance due to worse nonlinear performance. Full characterization of the gain provided by PCS modulation is therefore required in order to exactly quantify its SNR benefit in a realistic system, and whether this benefit overcomes the additional complexity it brings, when aiming to operate at low SNR (i.e. spectral efficiency).

In this paper, we perform a comparison between QPSK and PCS-16QAM operating at 128 Gbaud to achieve a net bitrate of 400 Gbit/s, therefore emulating the upcoming 400G transceiver generation for long-haul applications. This comparison takes into account the different penalty sources which affect the PCS gain, i.e. distribution matcher, FEC, tolerance towards fiber nonlinearities, digital signal processing (DSP) performance and transceiver SNR. We observe that, when accounting for the full system implementation, PCS-16QAM provides a limited SNR gain of about 0.1 dB.

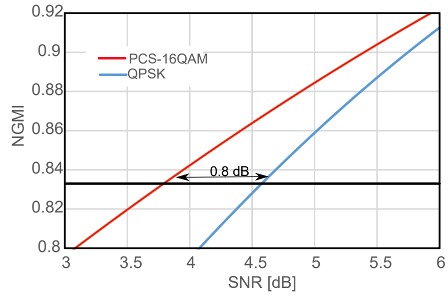

Fig. 1: NGMI for QPSK and PCS16QAM with entropy of 2.34 bit/symbol/polarization. The difference is measured at the theoretical NGMI limit of 1/1.2, which corresponds to 20% FEC overhead.

Experimental setup

The experimental setup is shown in Fig. 2. We generate a 128 Gbaud QPSK or PCS-16QAM signal in a 2-channel digital-to-analog converter (DAC) operating at 128 Gsample/s. In both QPSK and PCS-16QAM cases, 1 QPSK pilot symbol is inserted after 31 data symbols to enhance the DSP performance. Taking into account this $\sim$3.2% pilot overhead, we assume 20% FEC overhead and 3% protocol overhead to achieve a net bitrate of 400 Gbit/s. With all these overheads, the entropy, H, for PCS-16QAM is about 2.34 bit/sym per polarization, $H = OH_{\mathrm{prot}} \cdot R_{\mathrm{B}}/(2R_{\mathrm{S}}) + (m - m/OH_{\mathrm{FEC}})$ where $R_{\mathrm{B,S}}$ are the net bit and symbol rates, $m = \log_2(16)$, $OH_{\mathrm{prot,FEC}}$ are the protocol and FEC overheads[6],[8]. Digital pre-emphasis compensates for about 80% of the full transceiver bandwidth filtering. After amplifying each I and

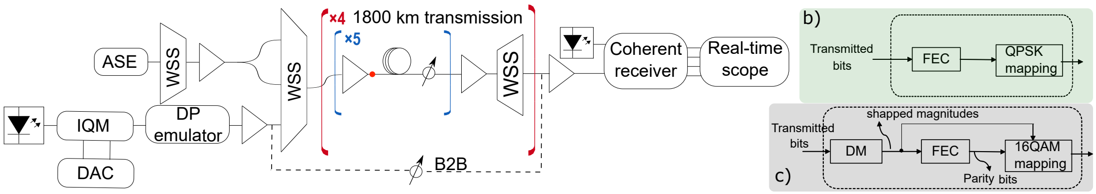

Fig. 2: Experimental setup. Architecture for b) QPSK and c) PCS-16QAM encoding and distribution matcher.

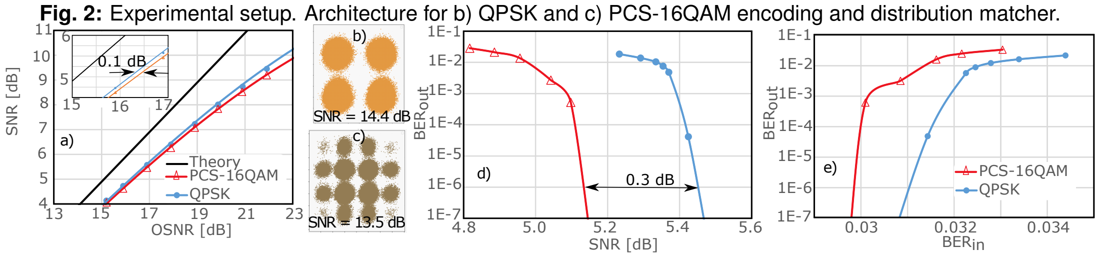

Fig. 3: Back-to-back experimental results, (a) Measured SNR vs OSNR. (b) QPSK and (c) PCS-16QAM constellations at the transceiver SNR ceiling. (d) BER after decoder vs measured SNR. (e) Output vs input BER of the decoder.

Q component, the optical carrier generated by a laser is modulated in an IQ modulator. The dual-polarization (DP) signal is then emulated by splitting the signal into two branches, delaying one branch and combining both branches with orthogonal polarization.

In the back-to-back (B2B) case (dashed line in Fig. 2) the signal is attenuated to perform noise loading. For transmission experiments, the signal is amplified before being multiplexed with another 10 WDM channels through a wavelength selective switch (WSS). These channels are emulated by shaping amplified spontaneous emission (ASE) noise with similar bandwidth as our channel under test, with the channel spacing set to 150 GHz. The number of channels is selected to be able to investigate the nonlinear tolerance of both choices. A larger number of channels would have prevented from reaching the optimum launch power due to the erbium-doped fiber amplifier (EDFA) power limitations. Our transmission link consists of 4 sections, each section containing 5 spans, whose characteristics are summarized in Tab. 1. As can be seen, in Sections 1, 2, and 3, the fiber type and the span loss are the same for the 5 spans, whereas the spans in Section 4 have different losses and a variety of fiber types, including SMF, large effective area fiber (LEAF), and True Wave reduced slope TW-RS (TW). The span losses are adjusted with an attenuator taking into account the gain range of the successive EDFA. After the last span of each section, a WSS is used to perform spectrum equalization. For simplicity, in this work, we flatten the signal spectrum at the input of the first span of each section.

After transmission, the channel-under-test is selected with the WSS placed at the end of Section 4. The signal is amplified with an EDFA, and then combined with the local oscillator in a

Tab. 1: Link settings

Section	1	2	3
Type	SMF	PSCF	PSCF
Length	80 km	100 km	100 km
Loss	22 dB	25 dB	25 dB

Section 4

Span	1&3	2	4	5
Type	SMF	SMF	LEAF	TW
Length	80 km	80 km	80 km	80 km
Loss	32 dB	21 dB	32 dB	32 dB

polarization-diverse coherent receiver. The electrical signals are then sampled by a real time oscilloscope operating at 256 Gsample/s. The DSP includes dispersion compensation, resampling, pilot-aided frequency-domain equalization, and frequency and carrier recovery.

Back-to-back results

In order to fully understand the benefits of PCS-16QAM over QPSK, we perform B2B measurements. For the PCS-16QAM generation, we include the distribution matcher (DM), implemented with the CCDM algorithm[9]. Additionally we also include the FEC with 20% overhead. We employ the probabilistic-amplitude shaping (PAS) scheme, as shown in Fig. 2(c)[8]. The magnitudes are shaped by the DM to achieve a pre-defined distribution, and the signs (polarity) are controlled FEC parity bits.

Figure 3(a) shows the SNR vs OSNR for both modulation formats. The performance is similar, but PCS-16QAM has approximately 0.1 dB SNR penalty at around the SNR limit for FEC operation. This difference is mainly due to the larger transceiver SNR ceiling of QPSK modulation due its lower peak-to-average power ratio (PAPR). The maximum measured SNR is 14.4 dB and 13.5 dB for QPSK and PCS-16QAM formats, respectively. This maximum SNR is limited by the

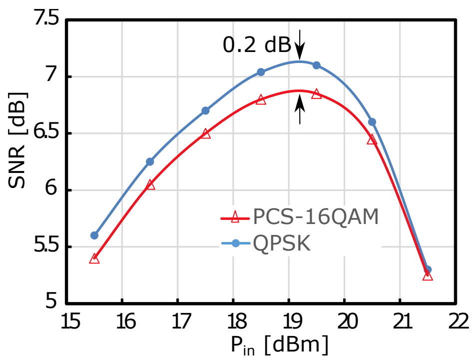

Fig. 4: Measured SNR vs total input power into each span.

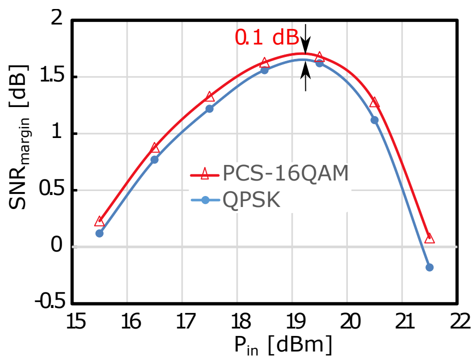

Fig. 5: Difference between the measured SNR and the SNR for error-free FEC operation.

amount of digital preemphasis which has been optimized for the low SNR region[10]. Figure 3(d) shows the BER after decoding with respect to the measured SNR. The predicted 0.8 theoretical difference between PCS-16QAM and QPSK is now reduced to 0.3 dB. This gap reduction is mainly attributed to the distribution matcher penalty and the FEC, including the different performance of the FEC for the different cases. Since we are referring to the measured SNR, the transceiver penalty is not taken into account in this plot. To better analyze the FEC penalty, we show the output vs input BER of the FEC decoder in Fig. 3(e). The different BERs required for error-free performance between PCS-16QAM and QPSK correspond to ∼0.05 dB SNR difference.

Transmission results

We also compare the performance of PCS-16QAM vs QPSK after 20 span transmission, corresponding to 1800 km. The launch power into each span is swept in order to find the optimum operation point. For simplicity, although it does not lead to the best performance, each span has the same input power. Figure 4 shows the measured SNR vs the input power. The SNR difference at the optimum launch power is ∼0.2 dB, which is 0.1 dB larger penalty than the one observed in the B2B experiment. Therefore, the additional penalty of PCS-16QAM over QPSK due to fiber nonlinearities is 0.1 dB (defined at the optimum launch power). This small difference would however be larger in low-dispersion networks. Through split-step Fourier simulations and EGN modelling we have confirmed that the expected nonlinear penalty is indeed 0.1 dB.

Once we have the SNR after transmission, we can calculate the margin between the measured SNR after transmission and the SNR required for error-free operation after the decoder, shown in Fig. 5. For this, we assume that FEC decoding will require the same SNR as in the back-to-back case. As can be observed, at optimum launch power PCS-16QAM provides 0.1 dB larger SNR margin than QPSK.

Discussion

We have experimentally quantified the SNR gain provided by PCS-16QAM over QPSK in a practical system, and found it to be 0.1 dB, which is 0.7 dB lower than the theoretical gain based on GMI. This loss is due to the different penalties of the full system implementation, such as transceiver performance (0.1 dB), fiber nonlinearity tolerance (0.1 dB) and FEC performance. The exact gap will also depend on the neighboring channels, which in this case have been generated by shaping of ASE noise. As an example, we have carried out simulations for a full QPSK WDM system, and found that the gain would drop by 0.1 dB, therefore nullifying any benefit of employing PCS-16QAM. Whether to implement PCS-16QAM or QPSK in an actual transceiver needs to take into account the SNR gain, but also the additional power consumption required by PCS-16QAM, since it requires the addition of the distribution matcher, while the FEC process twice the number of bits compared to QPSK. Another aspect to consider is that with PCS-16QAM it is possible to adjust the entropy, which in turn allows for a fine granularity on the symbol rate selection to achieve the same net bitrate. This can be especially useful to mitigate the effects of strong WSS filtering. On the other hand, in a QPSK system, the only option to reduce the symbol rate for filtering penalty reduction would be to reduce the FEC overhead. However, this is impractical, as transceivers typically have only a few FEC options.

Conclusion

We have compared PCS-16QAM and QPSK modulation formats for long-haul 400 Gbit/s transmission. We found that the theoretical 0.8 dB gain of PCS-16QAM is reduced to only 0.1 dB, after accounting for all practical system penalties.

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