Performance Comparison of Different 8QAM Constellations for the Use in Flexible Optical Networks

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Abstract: We investigate the influence of DAC resolution and pulse shaping on the system performance of different 8QAM constellations. Furthermore, we experimentally show that a circular constellation outperforms the commonly used 8QAM constellation by 0.7 dB in terms of OSNR sensitivity at a BER of $3.8 \cdot 10^{-3}$.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

Future flexible coherent optical transmission systems are expected to consist of format flexible transmitter and receiver units, which make use of digital to analogue converters (DAC) and analogue to digital converters (ADC). The DAC in the transmitter allows for digital pre-distortion and flexible generation of arbitrary modulation formats as well as for (Nyquist) pulse shaping to reduce the spectral width of the signal [1]. Using a coherent receiver, combined with format transparent data-aided digital signal processing (DSP), different kinds of modulation formats can be received and equalized with the same hardware setup [2, 3]. Such systems enable transatlantic transmission distances over optimized transmission links, even for advanced modulation formats like 16QAM [4]. However, when dealing with more challenging system configurations, including longer span lengths, more challenging fiber types or the absence of Raman amplification, 8QAM is a very interesting candidate as it is a compromise between spectral efficiency and transmission reach [5].

The performance of different possible 8QAM constellations towards Gaussian noise was already compared in 1974 [6]. Although the star-shaped (4,4) constellation, also known as star-8QAM, was found to be suboptimal in terms of noise performance, it is widely used in communication systems due to its simple generation with an IQ-modulator and the moderate number of five amplitude levels in the inphase and quadrature component. However, when taking into account DAC generated, pulse shaped and therefore analogue driving signals of future optical transmitters, combined with modulation format transparent receiver DSP, more complicated constellations and driving signal can be considered. The system performance of these more complex 8QAM formats depends on the actual implementation penalty. In this paper, we therefore investigate the performance of three different 8QAM constellations for the use in flexible optical networks, meaning format flexible transceiver units. The influence of the DAC resolution and the pulse shape on the performance of the different constellations is investigated by numerical simulations. In a second step, the performance of the three 8QAM constellations is compared in a system experiment.

2. Numerical Analysis

Figure 1 shows the constellations and the bit mapping as well as the symbol error rate (SER) and the bit error rate (BER) as a function of the OSNR for all three investigated 8QAM constellations at a symbol rate of 28 GBd.

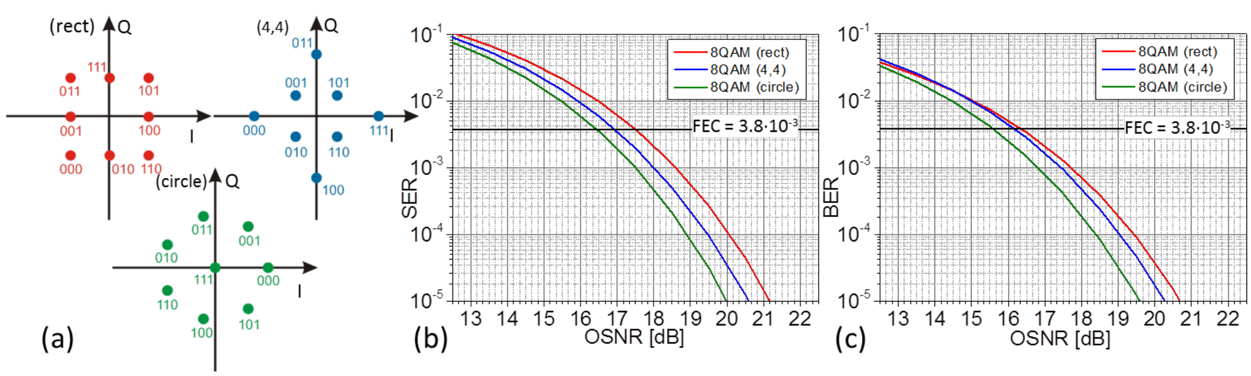

Figure 1: Different 8QAM constellations (red: rectangular, blue: (4,4) and green: circular). (a) shows the constellations and bit mappings, (b) the SER as a function of the OSNR and (c) the BER as a function of the OSNR. All results are shown for a symbol rate of 28 GBd.

These curves are generated by numerical simulations of ideal systems and additive white Gaussian noise (AWGN).The symbol error rates match the analytically obtained results in [6] and can therefore act as an upper bound of the system performance. The BER depends on the actual bit mapping and was evaluated with the mapping shown in Figure 1 (a). The mapping for the circular 8QAM was proposed in [7].

When comparing the SER of the different constellations in Figure 1 (b), it becomes apparent that the circular constellation performs best while the (4,4) and the rectangular constellations show worse performance. This is caused by the larger distances between the constellation points in the complex plane of the circular constellation, when considering the same average power. However, when comparing the BERs in Fig. 1 (c) instead, the performance differences decrease for low OSNR, because both the (4,4) as well as the circular constellation cannot be Gray coded in contrast to the rectangular constellation. The required OSNR (ROSNR) for the circular, (4,4) and rectangular constellations at a BER of $3.8 \cdot 10^{-3}$ are about 15.7 dB, 16.2 dB and 16.4 dB, respectively.

By looking at the constellations in Figure 1 (a), different numbers of amplitude levels of the inphase and quadrature component for the different constellations become visible. The rectangular and the (4,4) constellation require three and five amplitude levels, respectively for each quadrature, while the circular constellation requires five levels in the inphase and seven levels in the quadrature component. The different complexity of the driving signals will influence the performance of the systems when considering a limited DAC resolution. This behavior and also the influence of the pulse shape on the performance will be investigated in the following simulations.

For these simulations, the experimental back-to-back setup shown in Figure 3 (a) is emulated. Therefore the data bits are mapped onto the particular 8QAM constellation points and training symbols for frame synchronization, frequency offset correction and channel equalization are added as described in [3]. However, longer training sequences (sequence length of 64 symbols) were used, in order to enhance the frequency resolution of the channel estimation. Furthermore the training sequences are chosen from the data symbol alphabet of the particular 8QAM constellation. After that, a root-raised cosine filter with a variable rolloff factor as pulse shaping filter is applied, before the driving signals are linearly quantized with a variable number of quantization levels. Clipping was not considered throughout this paper. A model of an idealized dual-polarization (DP) IQ-modulator and a coherent optical frontend is used to emulate the modulation and reception of the optical signal. The linewidth used for the laser sources throughout the simulations was assumed to be 100 kHz. The DSP at the receiver consists of resampling to two samples per symbol, frame synchronization and data-aided channel equalization. As carrier phase recovery we used a Viterbi-Viterbi algorithm (the signal was raised to the 7^{th} power) for the circular constellation. Since this algorithm is not suitable for the other two constellation types, we used the blind phase search algorithm [8] for the rectangular and (4,4) 8QAM constellations.

The results of the numerical simulations at a symbol rate of 28 GBd are shown in Figure 2. They show the ROSNR at a BER of $3.8 \cdot 10^{-3}$ as a function of the DAC resolution for all investigated constellation types. When comparing the performance at high DAC resolutions, similar tendencies as for the ideal case (Fig. 1 (c)) are obtained. However, phase noise, filtering effects and DSP algorithms produce a small penalty ($\leq$ 0.4 dB). The penalties are slightly different for the individual constellations, ranging from 0.2 dB for the (4,4) up to 0.4 dB for the rectangular constellation.

Decreasing the resolution below about four bit results in significantly increasing penalties for all constellations. Furthermore, a smaller rolloff results in considerable higher peaks of the driving signals amplitude and therefore results, especially without clipping of the signal, in a decreased effective resolution for the data signal. This is the explanation for the worse performance of the smaller rolloff factors in the case of low DAC resolutions. The formats with less complex driving signals e.g. the rectangular 8QAM show an increased tolerance towards this effect.

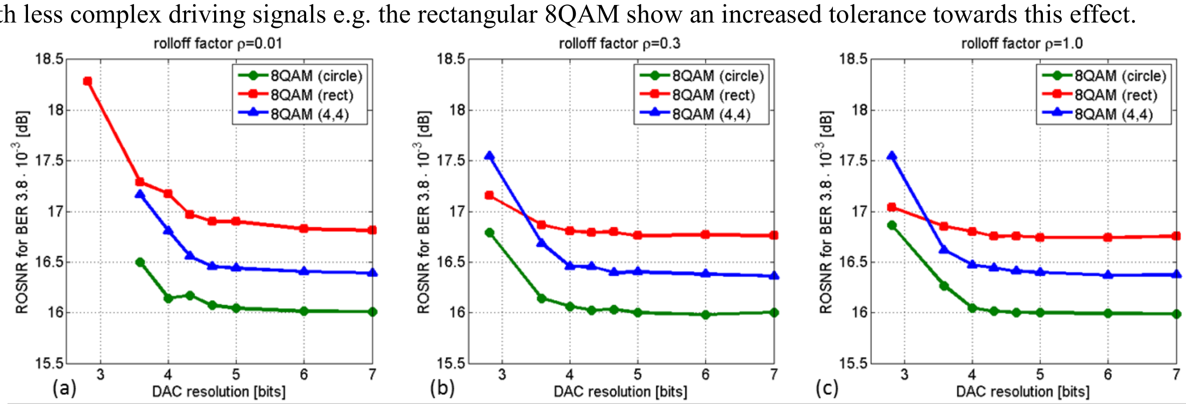

Figure 2: Required OSNR for a BER of $3.8 \cdot 10^{-3}$ as a function of the DAC resolution for all investigated constellation types. The individual graphs show different pulse shapes.

For a rolloff of 0.01 and low resolution for example, only the rectangular 8QAM is able to reach a BER below the FEC limit. Nevertheless, their worse baseline performance at high resolutions prevents them from outperforming the circular constellation. According to these simulations and assuming state-of-the-art DAC with an effective resolution of 4 bit and above, a circular 8QAM constellation therefore results in an increased performance compared to the commonly used (4,4) constellation. This holds true for all investigated rolloff factors of the pulse shaping filter. To verify these results, we performed an experimental investigation of the three constellations.

3. Experimental investigations

The experimental setup is depicted in Figure 3 (a). In the experiments we used a root-raised cosine pulse shaping filter with a rolloff factor of 0.01 and a linear pre-distortion in order to compensate for the frequency response of the DAC, the anti-aliasing filters and the optical modulator. The 28 GBd driving signals were generated with a 32 GS/s DAC with a 3 dB bandwidth of about 16 GHz and nominal resolution of 6 bit. The resulting electrical inphase and quadrature signals for the X polarization of all investigated constellation types are also depicted in Figure 3 (a). The large amplitude peaks due to the tight filtering and also the different number of amplitude levels for the individual constellations becomes visible. At the receiver, we used the same DSP algorithms as for the simulations, but additionally performed a correction of the imperfections of optical frontend and compensated for the frequency offset between transmitter and receiver laser.

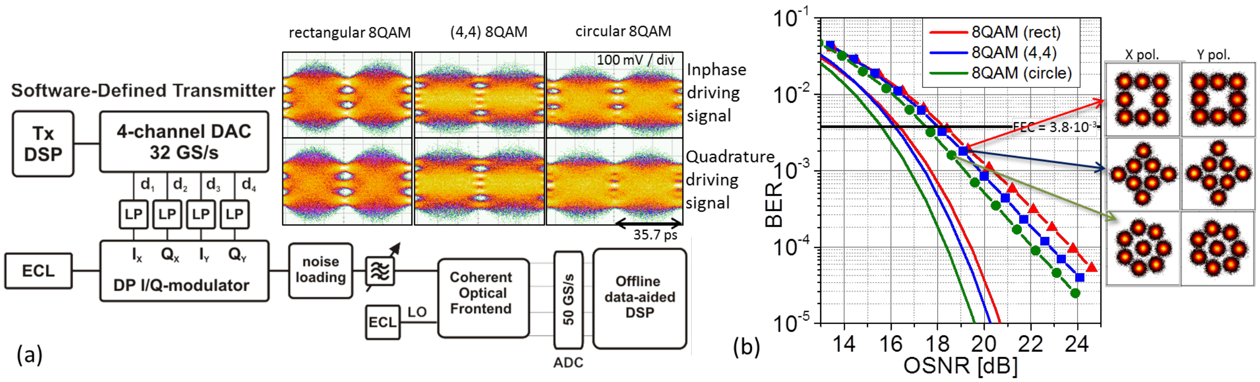

Figure 3: (a) Simulation and experimental back-to-back setup (ECL: external cavity laser, LO: local oscillator, BD: balanced detector, LP: low pass filter). Eye diagrams show experimentally recorded electrical driving signals of the X polarization. (b) Experimental results: BER as a function of the OSNR and corresponding received constellations for all investigated 8QAM constellation types.

Figure 3 (b) shows the measured BER as a function of the OSNR and the received constellation diagrams for all investigated 8QAM constellations. The implementation penalties compared to the AWGN simulations are similar for all 8QAM constellations (about 2 dB at a BER $3.8{\cdot}10^{-3}$). Similar to the simulations, the circular 8QAM performs best and shows about 0.7 dB and 0.9 dB better OSNR performance at a BER of $3.8{\cdot}10^{-3}$ than the (4,4) and the rectangular constellation, respectively.

4. Conclusion

We compared the performance of three different 8QAM constellations for the use in flexible optical networks. We investigated the influence of the DAC resolution and the pulse shaping on the different constellations by numerical simulations and verified the results in a back-to-back experiment. It was shown, that the circular 8QAM constellation outperforms the commonly used (4,4) 8QAM constellation by 0.7 dB in back-to-back scenarios with state-of-the-art components, even assuming pulse shaping and realistic DAC resolution.

5. Acknowledgement

This work has been supported by the FP-7 IDEALIST project under grant agreement number 317999 and by the German Federal Ministry of Education and Research (BMBF) in the CELTIC-plus program SASER under contract 16BP12402 (cluster ADVAntage-Net) and 16BP12310 (cluster SASER-Siegfried).

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