IPC 2017 – Orlando – Paper WH1.2

Impact of finite-resolution DAC and ADC on probabilistically-shaped QAM constellations

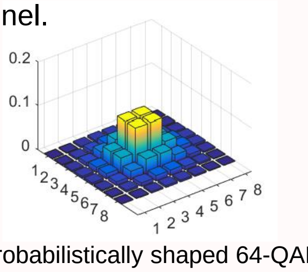
Dario Pilori(1), Chirs Fludger(2), Gabriella Bosco(1)

(1) Politecnico di Torino – Department of Electronics and Telecommunications, Italy

(2) Cisco Optical GmbH, Nuremberg, Germany

Introduction

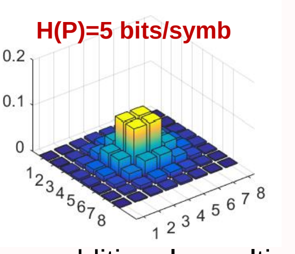
- Recently, Probabilistic Shaping (PS) has been applied to long-haul optical communication systems [1] to improve receiver sensitivity and increase transceiver flexibility.
- PS changes the a-priori probability of standard QAM constellations to mimic a Gaussian distribution, which is the optimal constellation in an AWGN channel.
- Using PS, lower energy (i.e. inner) points of a constellation are transmitted with higher probability than the other points.



- [1] J. Cho et al., "Transatlantic field trial using probabilistically shaped 64-QAM at high spectral efficiencies and single carrier real-time 250-Gb/s 16-QAM," in Proc. OFC 2017, Los Angeles, Mar. 2017, PDP paper Th5B.3.

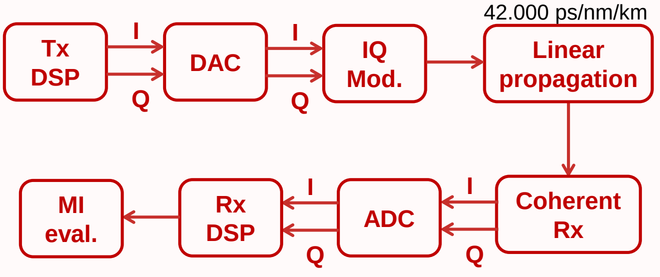
Introduction

- This reduces the net data rate, therefore, in order to keep the same bit rate as uniformly-distributed constellations, it is necessary to use higher cardinality modulations, such as 64- or 256-QAM.



- The use of larger constellations may induce additional penalties due to the finite resolution of DAC and ADC that are used to, respectively, generate and detect high-order modulation formats in a optical transmission system.
- In order to assess this penalty, we analyzed the performance of four different PS-64QAM constellations, comparing them to uniformly distributed constellations with the same net data rate.

Simulation set-up



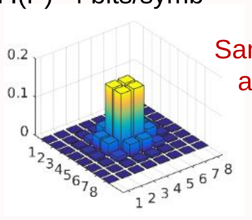
- The Mutual Information (MI) is evaluated using the Monte-Carlo approach:

$$MI = \frac{1}{K}\left[-\sum_{k=1}^{K}\log_2\left(\frac{1}{\pi\sigma_N^2}\sum_{x\in\chi}p_X(x)e^{-\frac{|y_k-x|^2}{\sigma_N^2}}\right)\right]-\log_2\left(\pi e\sigma_N^2\right)$$

- y_k is the received signal sample in the k-th time interval
- σ_N^2 is the noise variance
- K is the number of simulated symbols
- $p_X(x)$ is the probability of transmitting symbol x

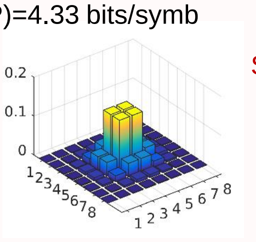
PS-64QAM constellations

H(P)=4 bits/symb



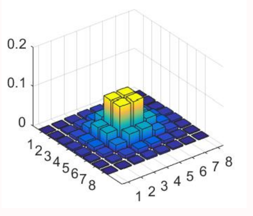
Same entropy as 16QAM

H(P)=4.33 bits/symb



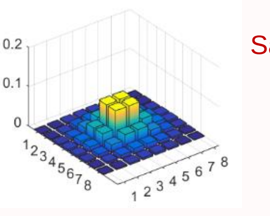
Same FEC rate as 16QAM

H(P)=5 bits/symb



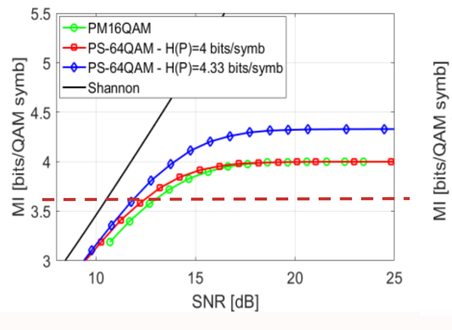
Same entropy as 32QAM

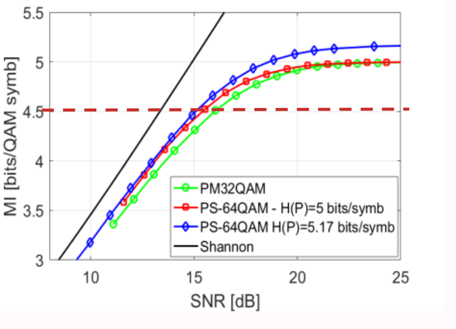
H(P)=5.17 bits/sym



Same FEC rate as 32QAM

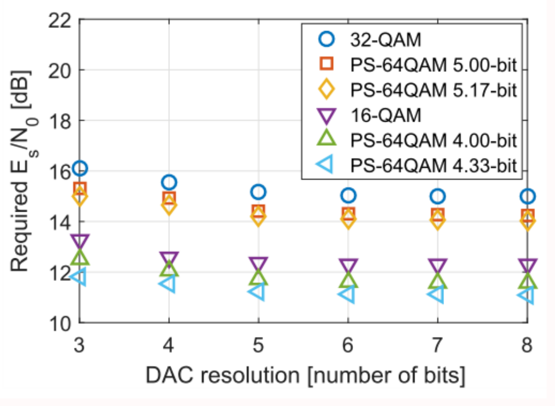
MI vs. SNR – Infinite DAC/ADC resolution





Entropy [bits/symb]	MI th. [bits/symb]	Sens. gain [dB]
5.00	4.5	0.80
5.17	4.5	1.02
4.00	3.6	0.85
4.33	3.6	1.29

Impact of DAC finite resolution



SNR PENALTIES WITH 4-BIT DAC

Constellation	SNR penalty [dB]
32-QAM	0.55
PS-64QAM 5.00-bit	0.67
PS-64QAM 5.17-bit	0.64
16-QAM	0.29
PS-64QAM 4.00-bit	0.49
PS-64QAM 4.33-bit	0.43

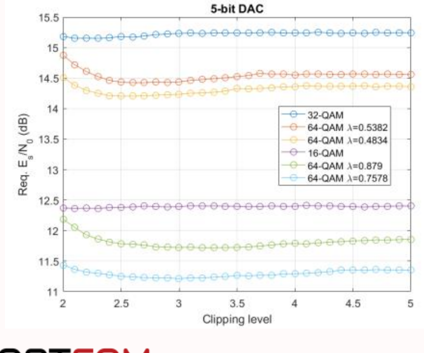
- Clipping optimized at every point.

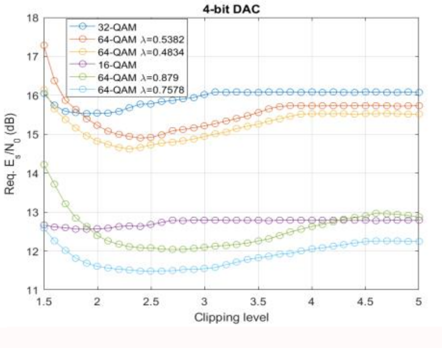
Effects of clipping – 4 and 5 bits DAC

- The clipping ratio μ is defined such that, for a real-valued signal $x(t)$:

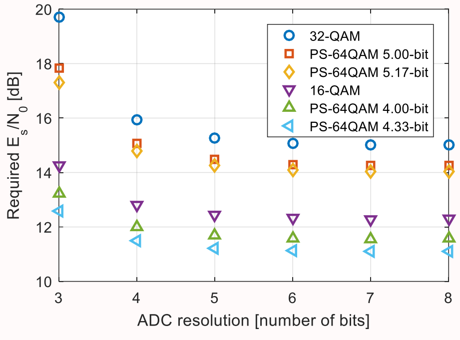
$$x(t) = \begin{cases} x(t) & |x(t)| \leq \mu\sigma_x \\ \mu\sigma_x \,\mathrm{sign}[x(t)] & |x(t)| > \mu\sigma_x \end{cases}$$

- σ_x is the standard deviation of $x(t)$
- For complex-valued signals, this operation is performed independently on the real and imaginary parts





Impact of ADC finite resolution

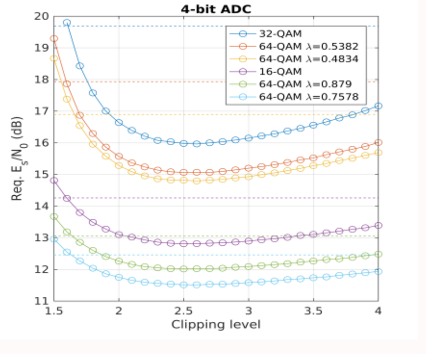


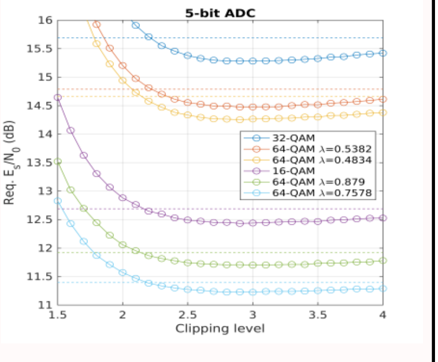
SNR PENALTIES WITH 4-BIT ADC

Constellation	SNR penalty (dB)
32-QAM	1.16
PS-64QAM 5.00-bit	1.06
PS-64QAM 5.17-bit	1.01
16-QAM	0.66
PS-64QAM 4.00-bit	0.71
PS-64QAM 4.33-bit	0.65

- Clipping optimized at every point.
- As opposed to DAC penalties, since all the constellations are Gaussian-like distributed, the penalty depends only on noise sensitivity of each constellation. For this reason, the penalty of PS constellations is similar or slightly smaller than the penalty of uniform constellations.

Effects of clipping – 4 and 5 bits ADC





- The SNR penalty due to quantization of the ADC can become very high in the presence of CD, if no clipping is applied.
- The penalty can be reduced to values close to the back-to-back penalty by applying the proper amount of clipping.

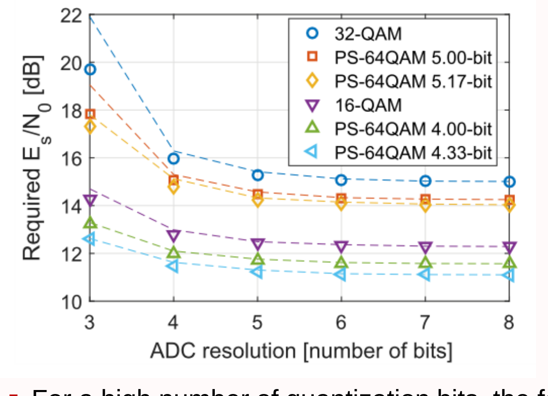
Quantization SNR at ADC

- At the ADC input, after fiber propagation, the received signal is impaired by chromatic dispersion. This changes the probability distribution of the signal to a Gaussian-like shape.
- It is therefore expected that the SNR penalty will not depend on the modulation format, but only on the target SNR.
- Assuming that quantization noise is uniformly-distributed, the quantization SNR can be calculated as:

$$\mathrm{SNR_q} = \frac{3}{\mu^2} 2^{2N_b}$$

  - Where μ is the clipping parameter and N_b is the number of resolution bits of the ADC.

Estimated performance – ADC finite resolution



$$\mathrm{SNR_q} = \frac{3}{\mu^2} 2^{2N_b}$$

$$\mathrm{SNR} = \frac{1}{\frac{1}{\mathrm{SNR}_{ASE}} + \frac{1}{\mathrm{SNR}_q}}$$

- For a high number of quantization bits, the formula predicts the SNR penalty with great accuracy, whilst for small number of bits the formula overestimates the SNR penalty.
- This is because quantization noise cannot be assumed uniformly-distributed with low number of quantization bits.

Conclusions

- We measured the SNR impairment of limited-resolution DAC and ADC on probabilistically-shaped 64-QAM constellations, comparing them with uniformly distributed modulations with the same net spectral efficiency.
- DAC penalties are slightly larger with higher-cardinality PS constellations.
- At the ADC side, due to chromatic dispersion, the received signal can be approximated as Gaussian-distributed and the penalty depends only on noise sensitivity of each constellation.

Impact of finite-resolution DAC and ADC on probabilistically-shaped QAM constellations

Dario Pilori[1], Chris Fludger[2], Gabriella Bosco[1]

(1) Politecnico di Torino – Department of Electronics and Telecommunications, Italy
(2) Cisco Optical GmbH, Nuremberg, Germany