Probabilistic vs. Geometric Constellation Shaping in Commercial Applications

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Abstract: We discuss performance and implementation aspects of geometric and probabilistic constellation shaping, which can be optimized for different applications. We show that symbol rate optimization with probabilistic shaping can further improve reach/capacity. © 2021 The Author(s)

1. Introduction

Constellation Shaping can operate closer to the theoretically achievable information rates by making constellations more Gaussian-like. There are two types of constellation shaping techniques: geometric shaping (GS) and probabilistic shaping (PS). Theoretically, both PS and GS can achieve up to 1.5 dB SNR gain, called shaping gain, for larger number of constellation points. These constellations are shaped to maximize tolerance to linear additive white Gaussian noise (AWGN). However, optical signals can incur nonlinear penalties during propagation in optical fiber due to Kerr effect, which can reduce shaping gain. Therefore, shaping should be designed for both linear and non-linear channel to maximize overall system gains.

In this paper, we discuss how to design and optimize constellations for the best performance with considerations of practical aspects of GS and PS. We also present symbol rate optimized PS-QAM technique which can maximize reach and SE x reach product in long-haul applications [1]. It can also optimize signal passband in ROADM dominated Metro networks [2].

2. Geometric Shaping (GS)

GS modifies the geometric location of the constellation points in Euclidean space to approach Gaussian-like distribution while keeping the same probabilities for all constellation points. The main advantage of GS is that we can design the constellation for improved tolerance to both linear and non-linear noise, which can increase system gain and enhance transmission reach significantly. Since the constellation design is fixed, it is hard to realize rate adaptivity. This makes GS an ideal candidate for niche applications where high performance is needed but rate adaptation is not required, e.g. long haul applications. On the other hand, the fixed rate has advantage of lower complexity circuit design because only a single fixed-rate data path is needed for a given client data rate, FEC rate, and modulation order.

In general, GS has no Gray mapping due to non-rectangular constellation, which may increase DSP complexity for de-mapping symbols and may incur mapping penalties. However, it is possible to design GS constellations with Gray mapping. One of the examples of such constellation is Gray labeled 4D-2A8PSK format [3]. It is optimized in 4 dimensions (4D) of the optical field and has higher tolerance to fiber Kerr nonlinearity due to 4D constant modulus constraint. It is commercially available and has simpler configuration and lower complexity compared to PS because it doesn't require distribution matcher.

Another example of 4D-optimized, Gray-mapped GS constellation designed for improved tolerance to Kerr nonlinearity is 64-ary polarization ring switching (4D-64PRS), which is still in research stage [4]. It shows the potential to outperform other GS formats. Also, GS constellation can be optimized for a given optical channel via end-to-end machine learning using neural networks (NN) [5-7]. In this case the joint optimization of transmitter and receiver NNs can be applied to overcome device and transmission imperfections and to maximize generalized mutual information (GMI). End-to-end learning is a powerful tool which can allow to customize GS constellations for each connection.

3. Probabilistic Shaping (PS)

PS modifies the probability of occurrence of constellation points in square QAM plane via Maxwell–Boltzmann (MB) distribution. PS can be implemented using probabilistic amplitude shaping (PAS) scheme, which combines distribution matcher (DM) and forward error correction (FEC) [8]. DM maps uniformly distributed input bits into the shaped amplitudes. After the DM, the amplitudes are mapped into QAM symbol stream. Thus, most of the state-ofart DSP algorithms developed for square QAM constellations can be re-used or modified. Constant composition DM (CCDM) was originally proposed with PAS architecture. It relies on arithmetic coding and requires long output block length (BL) to minimize rate loss, which adds complexity and latency. Other proposed DMs with lower complexity and smaller rate loss include enumerative sphere shaping (ESS) [9], multiset partition DM (MPDM) [10], hierarchical DM (Hi-DM) [11] and distribution matching by linear programming (DMLP) [12]. PS is commercially available. It requires more advanced DSP chip with DM and de-matcher compared to uniform QAM.

The main advantage of PS is the rate adaptation where both capacity and reach can be adjusted with fine granularity. However, variable rate adaptation brings higher complexity to circuit design because in addition to DM it requires multiplexing of fixed rate and variable rate data paths. On the other hand, PS in general has lower tolerance to fiber Kerr non-linearity due to modified constellation. Contrary to GS, where the constellation can be designed for nonlinear fiber channel, a DM must be designed for improved tolerance to non-linear noise. Recently introduced non-linearity tolerant ESS DM with short block length and low rate loss can deliver gains in both linear and non-linear regime, resulting in longer reach [9].

4. Symbol Rate Optimized PS-QAM

The reach of PS-QAM can be optimized by exploiting the flexibility in capacity or information rate (IR) of PS together with fine granularity in symbol rate (SR), which will be supported by the next-gen optical transponders. For example, for the same net data rate (DR), we can reduce IR of PS-QAM and increase SR as following:

$$DR = IR * SR = \{H - (1-c) * m\} * SR \quad (1)$$

The optimization of the *IR* can be done by optimizing signal entropy *H* for a fixed FEC rate *c* and modulation order $m = log_2 M$, where *M* is the cardinality size. The reduced *IR* is highly advantageous to extend transmission reach and lower *IR* signals can be transmitted at higher optimum signal power. From Shannon capacity theorem, the required SNR (RSNR) gain due to lower *IR* of PS-MQAM compared to reference IR (IR_{ref}) of a reference modulation format:

$$SNR\ gain\ [dB] = 10 \cdot log_{10}\left(\frac{2^{IR_{ref}-1}}{2^{IR-1}}\right) \quad (2)$$

Fig. 1 shows RSNR gain for the family of PS-QAM signals calculated from (2) vs. ratio of *SR* to the reference SR_{ref} (SR/SR_{ref}). In this work, the reference modulation format is uniform DP-16QAM ($m = 4$) with FEC code rate $c=0.8$ and IR_{ref} = 4*0.8=3.2 bit/sym/pol. The SR_{ref} is 32, 64 and 128 Gbaud for 200 Gb/s, 400 Gb/s and 800 Gb/s net data rates, respectively. The new SR/SR_{ref} metric allows to generate a universal plot of RSNR gain and corresponding IRs for all data rates and modulation formats. We see that theoretical RSNR gain of up to 14 dB can be achieved with this technique, where higher order QAM can reach larger gains due to lower IRs. And larger RSNR gains require larger SRs with respect to SR_{ref}.

However, current transceivers can support up to 100 Gbaud [13] due to limited bandwidth of analog devices at high symbol rates. Recent reports [14-18] demonstrate that the next-gen DAC/ADC can potentially support up to 192 Gbaud with reasonable implementation penalties, as shown in Fig. 2. By looking forward and assuming these penalties, we estimated reach of SR-optimized PS-QAM signals in 16-channel WDM transmission over N spans x 80 km SSMF fiber by simulation. Fig. 3 (a) and 3 (b) show reach extension and SE x reach improvement, respectively, at optimum SR for SR-optimized PS-QAM compared to non-optimized PS-QAM for 200, 400 and 800 Gb/s net data rates. The optimum SR exists due to trade-off between SNR gains and larger transceiver implementation penalties at high symbol rates. In addition, in case of SE x reach, an optimum SR exists due to reduced SE for large SRs.

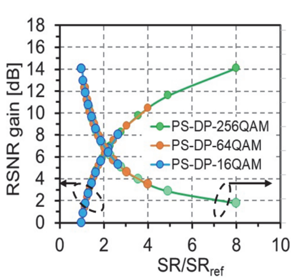

Fig.1. RSNR gain and IR due to optimized symbol rate

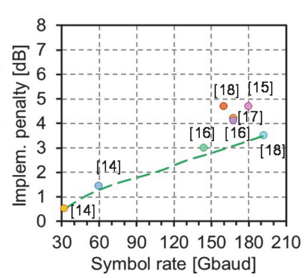

Fig.2. Transceiver implementation penalties.

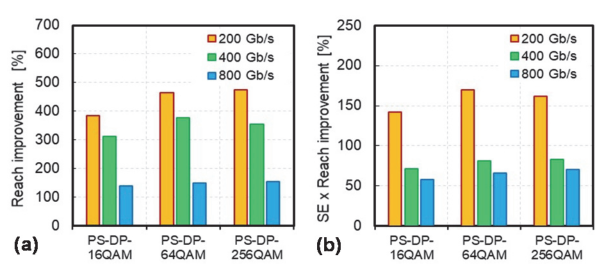

Fig. 3. (a) Reach and (b) SE x reach improvement of SR-optimized over non-SR-optimized PS-QAM systems.

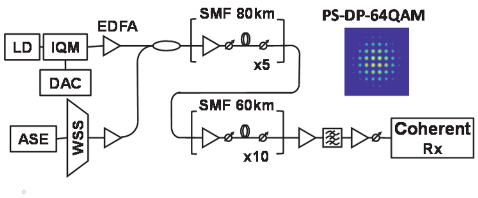

Fig. 4. Experimental set-up

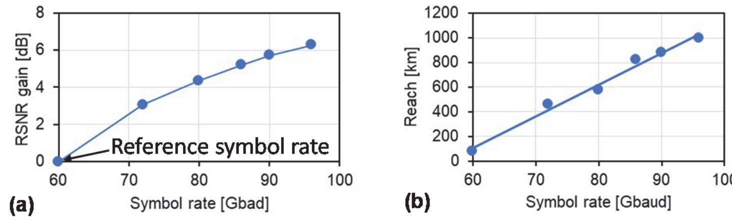

Fig. 5. (a) RSNR gain vs. symbol rate; (b) reach of SR-optimized DP-PS-64QAM

We observe significant improvements in reach and SE x reach for all data rates. In case of 800 Gb/s, SRs beyond 150 Gbaud are needed (where implementation penalties are large), thus, resulting in smaller percentage improvement.

In experiment, more practically implementable SRs were considered to evaluate the advantage of SR-optimization. The reference SR_{ref} and IR_{ref} are chosen as 60 Gbaud and 5.11 bit/sym/pol for 600 Gb/s data transmission. We transmit 44 WDM channels, where the center channel carries 600 Gb/s DP-PS-64QAM signal and the rest are ASE-loading channels with 75 GHz bandwidth (Fig. 4). We increase *SR* from 60 to 96 Gbaud and reduce *IR* from 5.11 to 3.19 bit/sym/pol to keep the same net data rate of 600 Gb/s. The channel spacing is 100 GHz for all symbol rates. Transmission line consists of 5 spans x 80 km and 10 spans x 60 km SSMF fiber. Each span loss is compensated by EDFA. Fig. 5 (a) shows measured back-to-back RSNR gain at NGMI threshold of 0.92 (FEC code rate of 0.87 and 0.05 coding gap) when SR increases from reference 60 Gbaud to 96 Gbaud. Fig. 5 (b) demonstrates that 1000 km can be achieved with 96 GBaud compared to only 80 km for 60 Gbaud 600 Gb/s DP-PS-64QAM systems. Similar dramatic increase in transmission reach was observed in [19-20].

5. Summary

We discussed the performance and implementation aspects of probabilistic and geometric constellation shaping. Both constellations can be optimized to achieve the optimum performance. GS has more flexibility to design the optimum constellation, while PS optimization is governed by Maxwell–Boltzmann distribution and is somewhat limited by the choice of distribution matcher. Further optimization of optical performance is possible for PS-QAM via SR-optimization, which can significantly increase transmission reach and improve SE x reach product. This optimization (perhaps with coarse granularity) can be applied to GS if transponder can support IR-switchable GS constellations.

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