Practical Considerations for Geometric and Probabilistic Shaping in Optical Communication Systems

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Abstract *We discuss performance and implementation aspects of geometric and probabilistic constellation shaping. We demonstrate how rate adaptivity of PS has made it a very powerful tool for optical communications industry regardless of its higher implementation complexity.*

Introduction

It's been ten years since constellation shaping was first introduced to optical communications. It became possible due to availability of optical coherent detection with advanced digital signal processing (DSP). The first reports appeared back in 2013-2014 [1-2], where geometric shaping (GS) was introduced. GS modifies the density of constellation points and requires more complicated mapper/demapper, encoder/ decoder techniques. Nevertheless, the advantages of constellation shaping were immediately recognized. This paved the way for the development of lower complexity geometric shaping and, more importantly, to probabilistic shaping. Probabilistic shaping (PS), which modifies the probability of occurrence of constellation points in square QAM, was first proposed in 2014 [3]. It was based on many-to-one mapping and, thus, required complex iterative demapping. But the real recognition of PS has occurred after the introduction of probabilistic amplitude shaping (PAS) architecture by G. Bocherer in 2015 [4]. PAS delivers an elegant solution to separate FEC from shaping by concatenating a distribution matcher (DM) and systematic binary forward error correction (FEC) encoder. At the receiver, a bit-wise demapper is simply followed by binary decoder without need for iterative demapping. Constant composition DM (CCDM) with fixed-to-fixed mapping between input bit sequences and output codewords was introduced in [5]. In PAS, the rate adaption can be achieved by adjusting symbol distribution via entropy, FEC rate and QAM modulation order. The first experimental demonstration of rate adaptive PS-64QAM with more than 40% reach increase compared to uniform 16QAM and 64QAM was reported in [6].

Today, the advantages of PS are well understood and recognized by telecommunication industry. PS has become an industry-wide accepted modulation format and an integral part of DSP of coherent transceiver according to the most recent product release announcements made at OFC 2023 [7-10]. PS can bring an unprecedented flexibility in configuring the information rates (IR) and data rates per transmission link to enable truly adaptive optical networks.

In this paper, we present the practical aspects of both GS and PS and discuss what makes PS such a popular modulation format among other choices.

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. GS can achieve up to 1.5 dB SNR gain (shaping gain) for larger number of constellation points, when optimized for linear additive white Gaussian noise (AWGN) channel. 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 cardinality 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. 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 labelled 4D-2A8PSK format [11]. 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 [12].

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 [13]. 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) [14-17]. 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 could be a powerful tool which can allow to customize GS constellations for each connection.

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 FEC [4]. 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 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) [18], multiset partition DM (MPDM) [19], hierarchical DM (Hi-DM) [20] and distribution matching by linear programming (DMLP) [21].

The main complexity of PS is that it requires more advanced DSP chip with DM and de-matcher. On the other hand, the main advantage of PS is the rate adaptation where IR can be tuned with fine granularity. This variable rate adaptation brings an additional complexity to circuit design because in addition to DM it requires multiplexing of fixed rate and variable rate data paths. Nevertheless, the ability to fine tune IR and, thus, data rate for each fiber link plus the shaping gain (up to 1.53 dB) brings unprecedented flexibility in designing optical networks with maximized capacity and reach.

This makes PS a very powerful tool for optical communications industry. PS is commercially available and has become an integral part of modern coherent transceivers [7-10].

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 nonlinearity 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 [18].

Capacity-Reach Optimization

The capacity-reach optimization is essential in designing the optimal communication channel. The reach of PS-QAM signals can be maximized by exploiting its flexibility in IR (capacity in bit/sym per polarization) and data rate. Another degree of flexibility can be achieved with fine granularity in symbol rate, which will be supported in recently announced optical transponders [7-10]. Thus, joint optimization of IR and SR can be done to either keep the same data rate or flexibly change the data rate.

For the same net data rate (DR), we can reduce IR of PS-QAM and increase SR as following:

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

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 of MQAM signal. Reducing *IR* is highly beneficial to extend transmission reach because it reduces the required SNR (RSNR), according to Shannon capacity theorem. And lower IR signals can be transmitted at higher optimum launch power.

We experimentally demonstrated the advantage of joint SR and IR optimization [22]. The significant reach increase of 600 Gb/s PS-DP-64QAM signal was observed, when we increased SR from 60 to 96 GBaud and reduced IR from 5.11 to 3.19 bit/sym/pol, respectively, to keep the same net data rate of 600 Gb/s (see Fig.

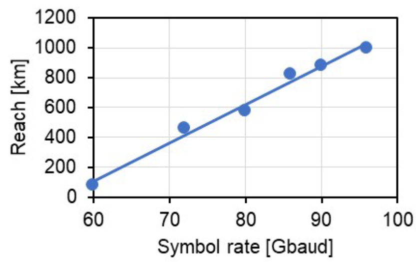

Fig. 1: Transmission reach increase due to SR and IR optimization for 600 Gb/s DP-PS-64QAM.

1). And we kept the same 100 GHz channel spacing for all symbol rates.

The flexibility in IR and SR can be also exploited in ROADM dominated networks, where filtering may limit transmission performance. One way to minimize the impact of filtering is to assign a spectral guard band *Δf* between the edges of the signal and allocated slot for a given channel, as shown in Fig. 2. Moreover, for the same slot width, data rate, spectral efficiency, and guard band we can transmit either single carrier, or multi-carrier signals. For example, the next generation systems must support 1.6 Tb/s. Single carrier 1 x 1.6 Tb/s operating at higher symbol rates (about 250 GBaud) is preferable solution due to reduced cost per bit and simplified network operation. However, higher symbol rate signals are more affected by limited bandwidth of analog devices. Current transceivers can support up to 135 GBaud capabilities [7-9]. Recent research is focusing on symbol rates as high as 256 GBaud [23]. On the other hand, transmitting a superchannel with 2 x 800 Gb/s subcarriers at lower symbol rates, which are commercially available, is another viable solution. In these two cases, the spectral occupancy of 1 x 1.6Tb/s and 2 x 800Gb/s channels maybe different. In superchannel generated by two lasers, some subcarrier spacing *Δsc* would be needed to minimize linear crosstalk due to laser frequency stability. In this case, 1 x 1.6 Tb/s signal can occupy larger bandwidth for the same *Δf*, compared to 2 x 800Gb/s signals. In both cases, we can fine tune SR and IR of PS-QAM to maximize transmission reach for the same *Δf*.

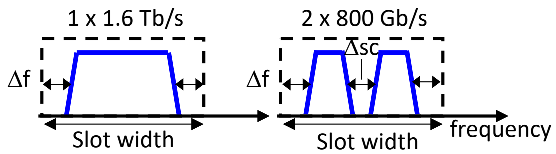

Fig. 2: Channel configurations for 1.6Tb/s.

Fig. 3 (a) demonstrates that 1 x 1.6Tb/s PS-DP-64QAM signal with joint optimization of SR and IR can deliver 50 km longer reach for various guard band values *Δf* compared to 2 x 800Gb/s configuration with subcarrier spacing Δsc = 3.6 GHz. The slot width is 275 GHz. We varied symbol rates from 120 GBd to 127 GBaud for 800Gb/s signals and from 243 to 257 GBaud for 1.6 Tb/s, depending on *Δf*. Transceiver implementation penalty due to larger SR is not considered in this work. PS-DP-64QAM signal is Nyquist pulse shaped with roll-off factor 0.05. Maximum reach was calculated using closed-form EGN model for 11-channel WDM system with multiple spans of SSMF fiber [24].

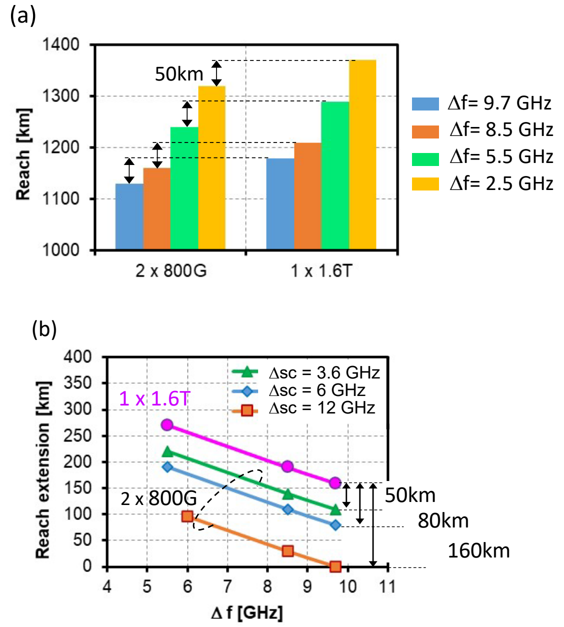

Fig. 3: (a) Transmission reach of 2 x 800G and 1 x 1.6 T depending on different guard band values taken for the same subcarrier spacing Δsc = 3.6 GHz; (b) Reach extension of 1 x 1.6 T over 2 x 800G PS-DP-64QAM for various Δsc values

Fig. 3(b) shows reach extension of 1 x 1.6Tb/s and 2 x 800Gb/s PS-DP-64QAM signals for various subcarrier spacing Δsc and Δf values, where allowable Δf should be *Δf ≥ Δsc/2* to avoid linear crosstalk. Larger Δsc reduces spectral occupancy of 800G signals, resulting in shorter reach and, thus, increasing reach gain of 1 x 1.6 Tb/s. This demonstrates the advantage of single carrier 1.6 Tb/s signal with symbol rates up to 257 GBaud in ROADM dominated networks. Moreover, joint optimization of SR and IR, which is possible with rate adaptable PS signals, is essential for maximizing capacity and reach.

Conclusions

We discussed the implementation aspects of probabilistic and geometric constellation shaping. Both constellations can take advantage of the shaping gain and can be optimized to achieve the optimum performance. GS has more flexibility to design optimum constellation with fixed information rate, which makes it a good candidate for niche applications. PS has more flexibility to design QAM constellation with finely tuneable IR for each fiber link. This makes PS an ideal candidate for development of adaptive optical transport networks with maximized capacity and reach. As a result, PS has become an industry-wide accepted modulation format and an integral part of DSP of coherent transceiver.

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