Probabilistic and Geometric Shaping for Next-Generation 100G Flexible PON

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Abstract *We investigate probabilistic shaping (PS) and geometric shaping (GS) for next-generation flexible passive optical network (PON) systems. Our proposed scheme introduces flexible data rate tuning with up to 1.1-dB sensitivity improvement, while GS can effectively mitigate the penalty brought by combination with forward error correction (FEC).*

Introduction

Recent years have seen a widespread increase in research into next generation optical access systems to support transport of diverse applications like 8K video, 5G mobile data, and internet of things. PON, due to its passive point to multiple point architecture, has the promise to transport all of these in a cost-effective way[1]. Also, existing PON networks already provide a substantial footprint that operators can tap into. However, up till now PON standards have employed a fixed data rate designed for the worse-case channel conditions. This leads to sub-optimal resource utilization. To allow for more flexibility to support the disaggregation of network functions in the optical transport layer and to better utilize resources, we investigate how to flexibly adapt the data rate of next generation PON systems depending on channel conditions of the users.

A straightforward way to flexibly adjust the data rate is to change the modulation order (e.g., NRZ, PAM4, and PAM8) for the different users. However, entropy tuning using uniform-distributed signals is stepwise and improvement is hampered by the large sensitivity difference between different modulation formats[2]. Therefore, we propose to adopt PS for continuous, flexible entropy tuning with enhanced noise tolerance. In the last few years, PS was a hot research topic in fiber optical and copper access networks[3]. Most of the work studies bipolar Maxwell-Boltzmann distribution to approach Shannon capacity with improved shaping gain, which is developed for additive white Gaussian channels constrained by a fixed second moment of the transmit signals as is applicable in many coherent and multi-carrier systems[3,4]. However, the considerations are different for intensity modulation and direct detection (IM-DD) systems. Some research papers have investigated IM-DD systems using unipolar exponential distribution by maximizing the entropy[5] in data center applications. However, since PON has specific requirements including large power budgets (min 29 dB) and using APDs, the interaction with noise (e.g., shot noise and thermal noise) and link budget optimization are still not well studied.

In this paper, we therefore investigate PS specifically for PON in an IM-DD single-carrier system. The system includes a Semiconductor optical amplifier (SOA) at the transmitter side, which is considered necessary for next-generation PON systems (G.hsp) to boost the link budget. In this study, the SOA also serves as a critical component to decouple the modulator output power dictated by PS and GS, and the final transmitter output power for link budget optimization. The receiver consists of an avalanche photodiode (APD) and a trans-impedance amplifier (TIA). We also introduce GS to compensate for the penalty from combination with FEC. Our scheme achieves continuous rate tuning and up to 1.1-dB sensitivity improvement over uniform-distributed PAM signals. We also verify the feasibility of continuous spectral efficiency (SE) tuning using Monte Carlo simulations with a practical FEC. To the best of our knowledge, this is the first study of applying PS and GS to next-generation PON systems.

Principle of Operation

Assume the transmitted data is X and the received data is Y, the achievable rate can be characterized as Generalized Mutual Information (GMI) R_{BMD} :

$$\mathrm{R}_{BMD} = \max(\, \mathbb{H}(X) - \sum \mathbb{H}(\mathrm{B}_i \,|\, \mathrm{Y}),\ 0), \tag{1}$$

where B_i represents the ith bit of the symbol. In our case, GMI is calculated based on Gray mapping. Assume α is the E/O coefficient of modulator, G is the SOA gain, and P_{avg} is the average output power from SOA. The optimization problem is formulated as:

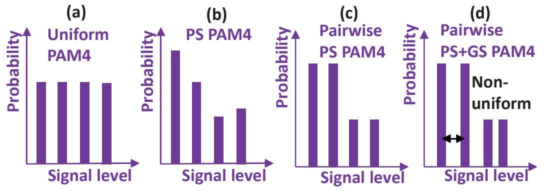

Fig. 1: (a) to (d) Illustration of the investigated schemes using PAM4 as an example.

$$\begin{aligned} &\max_{P_x, S_x} \ \mathrm{R}_{BMD} \\ &\text{subject to } \mathbb{E}\left[\alpha \cdot G \cdot \mathrm{X}\right] = \alpha \cdot G \cdot \sum P_x \cdot S_x = P_{avg}, \\ &\qquad \max(\alpha \cdot G \cdot \mathrm{X}) \le X_{th}, \text{and NGMI} \ge \mathrm{R}_{th}, \end{aligned} \tag{2}$$

which is solved by the interior-point method. To avoid local maxima, we run the algorithm five times with random starting points. P_x and S_x denote probability distribution from PS and signal levels from GS. X_{th} is SOA peak power threshold to maintain linear operation. R_{th} is the Normalized Generalized Mutual Information (NGMI) threshold considering practical implementation. NGMI corresponds the maximally usable FEC code rate with ideal binary FEC decoding and is expressed as[6]:

$$NGMI = 1 - \left(\mathbb{H}(X) - R_{BMD}\right)/m, \tag{3}$$

where m denotes bits per symbol (e.g., 2 for PAM4, 3 for PAM6/8). A practical FEC code has a gap Δ between its code rate R_c and the NGMI threshold R_{th}: $R_c = R_{th} - \Delta.\ (\Delta \ge 0)$.

Fig. 1 illustrates the schemes investigated in this paper using PAM4 as an example. Fig.1 (a) shows Uniform PAM4 and (b) indicates a typical optimal probability distribution. The distribution is neither symmetric nor monotonic. The asymmetry makes it unsuitable for conventional serial combination with FEC or probabilistic amplitude shaping since FEC parity bits are typically uniformly distributed. Therefore, we use pairwise distribution[7] (Fig. 1(c)) that insert the parity bits in the least significant bit (LSB). A distribution matcher (DM) generates the shaped pairs (e.g., 2 pairs for PAM4 and 4 pairs for PAM8). Parity bits placed in the LSB distinguishes the two levels in each pair with the same probability, thus preserving the DM distribution. The pairwise constraint introduces a minimal code rate and thus minimal NGMI requirement as:

$$\mathrm{NGMI} \ge \mathrm{R}_{th} = (\mathrm{m}-1)/m. \tag{4}$$

However, the pairwise constraint introduces a performance penalty compared to the optimal distribution. Therefore, we propose to use GS (Fig.1(d)) to mitigate the penalty due to pairwise distribution. Moreover, we also investigate PS-PAM6, which is a reduced PS PAM8 by removing two levels from PAM8[5].

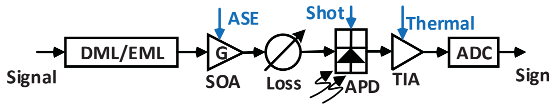

Fig. 2: Simulation block diagram.

Simulation Setup

Fig. 2 presents the 50-Gbaud simulation block diagram. The extinction ratio of an externally-modulated laser or a directly modulated laser is set to 6 dB. The peak optical modulator output power is 4 mW and the minimum signal level is 1 mW. An SOA with 7 dB noise figure boosts the modulator output with variable gain (G). The SOA input SNR is 45 dB. The SOA output power (P_{avg}) is 6 dBm and SOA peak power threshold X_{th} is 10 dBm. The transmitter resolution is 8 bits and ADC resolution is 6 bits. Optical losses mainly arise from splitter loss and fiber loss. At the receiver side, the signal is detected based on square-law detection with signal-dependent shot noise and thermal noise. APD gain (M) is 8, responsivity is 0.7A/W @M=1 and ionization factor is 0.13. TIA input-referred noise is 11 pA/sqrt(Hz). The signal bandwidth is assumed to be 25 GHz. The simulation is conducted under the assumption of linear operation range, perfect clock recovery and channel information, and no fiber dispersion.

Results with flexible FEC code rate tuning

Firstly, we optimize the GMI without pairwise and NGMI threshold constraint. Fig. 3(a) presents the GMI of PS+GS signals. Compared with Uniform PAM4 at GMI of 1bits, PS signals exhibit 1.1-dB sensitivity gain and 0.18-bits GMI improvement. Compared with Uniform PAM8 at GMI of 2 bits,

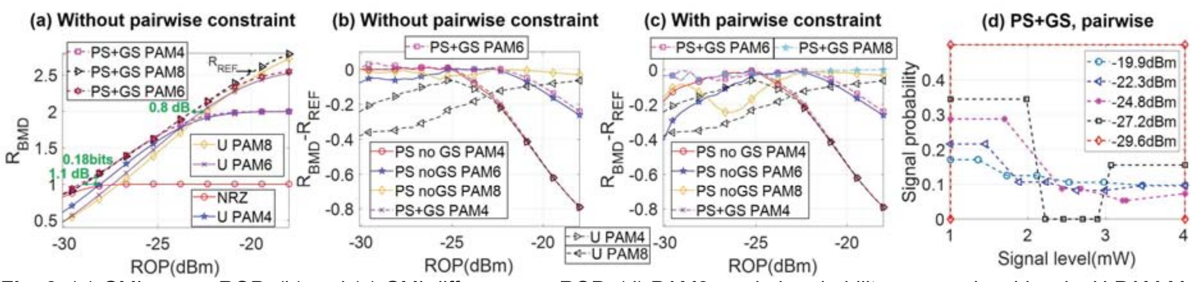

Fig. 3: (a) GMI versus ROP. (b) and (c) GMI difference vs ROP. (d) PAM8 symbol probability versus signal levels. U PAM-M: Uniform distributed PAM-M.

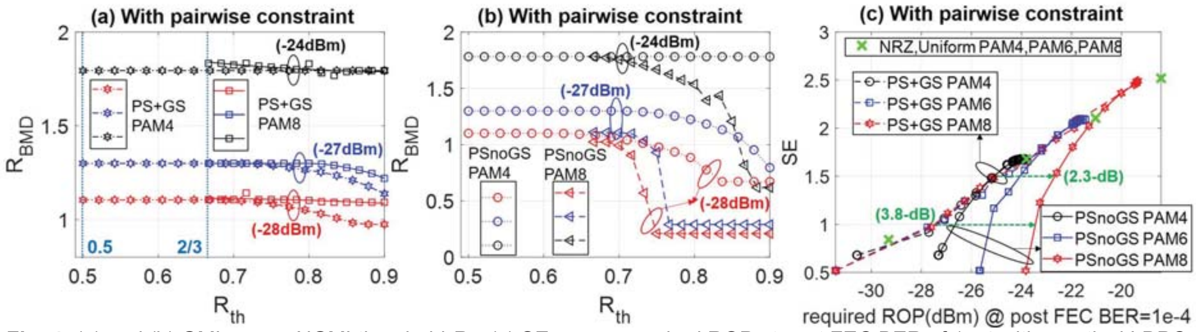

Fig. 4: (a) and (b) GMI versus NGMI threshold R_{th}. (c) SE versus required ROP at post FEC BER of 1e-4 with practical LDPC.

PS PAM8 shows 0.8-dB sensitivity gain and 0.12-bits GMI improvement. We also plot the GMI difference between other settings and reference GMI (R_{REF}, GMI of PS+GS PAM8) in Fig.3 (b), where GS offers <0.05-bits GMI improvement compared to no GS settings.

Next we compare the signals with pairwise constraint by plotting the difference between GMI and R_{REF} as shown in Fig. 3(c). In this case NGMI has constraints defined by Eq (4) (0.5 for PAM4, 2/3 for PAM6 and PAM8). Different from no pairwise setting, GS offers significant GMI improvement (up to 0.2 bits for PAM4, 0.4 bits for PAM6, 0.25 bits for PAM8) compared to no GS setting. No GS setting even performs worse than uniform signals for some lower ROPs. Meanwhile, with GS, the GMI nearly overlaps with R_{REF}, which means GS can compensate for the penalty from pairwise distribution.

Fig. 3(d) presents the optimized PS and GS PAM8 results with pairwise constraint. PS tends to assign higher probabilities to symbols with less power, this reduces the modulator output power and requires an increase in SOA gain to maintain the same SOA output power. As the ROP decreases, the signal transitions to fewer levels by setting probabilities of some levels to 0 or merging some symbols into the same signal level. Moreover, GS tends to move symbols with higher probability away from one another. Table 1 summarizes the SOA gain of pairwise GS+PS PAM8 versus ROP, which shows higher gain over the Uniform signal (fixed at 2 dB).

Results with fixed FEC code rate

In the case of pairwise constraint, we also sweep the NGMI threshold R_{th} considering a fixed FEC code rate implementation as shown in Fig. 4(a) and (b). PAM4 starts from $R_{th}=0.5$ while PAM8 starts from 2/3. Without GS, the signal starts to degrade from $R_{th}=0.68$. The signal with GS shows degradation when R_{th} is larger than 0.78, and thus is less sensitive to the increasing of R_{th} compared to signal without GS.

Tab. 1: SOA gain of PS+GS PAM8 with pairwise vs ROP

ROP (dBm)	-18	-22	-26	-30
Gain(dB)	2.45	2.66	2.65	2

Next we consider Monte Carlo testing with the IEEE 802.3ca LDPC code[8] with a fixed code rate (R_c) of 0.84. According to the results of Uniform PAM, the gap between NGMI and R_c is $\Delta \approx 0.05$ at a post-FEC BER of 1e-4, which was chosen relatively high to make the simulation time feasible. Based on this observation, we perform the optimization with $R_{th}=R_c+0.05=0.89$. With the optimized GS and PS settings, we run Monte Carlo testing to check the SE versus required ROP at the post FEC BER of 1e-4. Here the parity bits are inserted in the LSB of the DM output. LDPC decoding is realized by descrambling the LLRs to all zero-codewords at the receiver. SE is defined as $SE=\mathbb{H}(X)-(1-R_c)\cdot \mathrm{m}$. Fig.4(c) demonstrates that the proposed scheme always outperforms uniform signaling when the signal entropy is non-integer with continuous SE tuning. GS shows 3.8-dB and 2.3-dB sensitivity improvement compared to PS PAM8 without GS when SE=1 and 2 bits. PS PAM8 covers most of the ROP ranges and outperforms Uniform PAM6 by 0.5 dB at SE=2.105 bits. PS PAM4 outperforms PS PAM8 by up to 0.1-bits/channel improvement from -25dBm to -24dBm.

Conclusion

We have provided the first investigation of applying PS and GS to enable next generation flexible line-rate PON. PS and GS was studied and optimized specifically for PON under the impact of different noises. With GS, the pairwise distribution can preserve the distribution from DM with comparable performance to the optimal results without constraints. In the case of flexible FEC code rate adjusting, the proposed scheme demonstrated up to 1.1-dB sensitivity gain and 18% net data rate improvement compared with uniform PAM4. PS PAM8 gives the optimal GMI among typical PON operating ranges. Monte Carlo simulation using practical LDPC also proved its feasibility to achieve flexible SE tuning with a fixed FEC code rate.

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