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Irregular QAM Formats for Short-Reach Amplifier-Less Coherent Optical Systems

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Abstract *A low-complexity scheme is proposed to realize irregular QAM formats in amplifier-less coherent optical systems. The simulation results show 36QAM and 49QAM achieve 2.32 dB and 1.9 dB gains of power budget over 64QAM at net bit rates of 650 Gbit/s and 750 Gbit/s, respectively. ©2022 The Author(s)*

Introduction

The traffic within data centers has been growing rapidly due to the development of internet-based applications. This has driven the increased capacity demand of short-reach optical transmission systems. To improve the system capacity, cost-effective coherent optical systems are considered to be promising solutions in short-reach applications which have a high requirement on power-consumption and cost [1, 2]. Removing optical amplifiers is able to reduce the cost of the system, but it poses a challenge on power budget [3, 4].

Probabilistic shaping (PS) has been widely investigated in coherent optical systems with optical amplifiers [5-9]. PS is able to achieve a larger power efficiency over conventional uniform signals and to realize data rate adaptation. However, limited by the peak-power constraint in amplifier-less optical systems, PS with Maxwell-Boltzmann (MB) distribution shows worse performance compared to uniform signals [10]. The optimal probability distribution of PS has been studied in amplifier-less coherent systems and it is shown the signals with quasi-uniform distributions tend to achieve the best performance [11]. Although PS can be used to realize the quasi-uniform distributions, it can only realize $4M^2$-ary quadrature amplitude modulation (QAM) formats by truncating the outside symbols, where M is an arbitrary integer. The implementation complexity may be still high especially for high order modulation formats.

In this paper, we propose a low-complexity scheme to realize irregular QAM modulation formats with modulation orders of M^2. To the best of our knowledge, this is the first time to realize arbitrary M^2-ary QAM formats with Gray mapping. Compared to conventional QAM formats, this scheme provides a more flexible rate adaptation to the underlying systems with a fixed forward error correction (FEC). The performance is demonstrated in simulations and the results show compared to 64QAM, 36QAM and 49QAM achieve 2.32 dB and 1.9 dB gains of power budget at net bit rates of 650 Gbit/s and 750 Gbit/s, respectively.

Principle

The architecture of the proposed scheme to realize irregular QAM formats is shown in Fig. 1(a). The architecture is similar to that of probabilistic amplitude shaping [6], while the detailed process is different. We take 49QAM as an example to illustrate the detailed process, which is depicted in Fig. 1(b).

49QAM has 7 amplitudes and each amplitude has a probablity of 1/7. We divide the 7 amplitudes into three groups with 4, 2 and 1 amplitudes, respectively. The corresponding probabilities of the three groups are 4/7, 2/7 and 1/7, respectively. With additional two and one uniform bits to combine with the first two groups, respecitively, we can obtain 7 amplitudes whose probabilities are all 1/7.

As shown in Fig. 1(b), the uniform information bits are devided into two parts. Information bits I enter constant compostiion distribution matching (CCDM) encoder [12] and the output blocks are with a fixed probability distibution of (4/7, 2/7, 1/7). The output symbols 0, 1 and 2 with probabilities of 4/7, 2/7 and 1/7 are labeled by bit ‘0’, ‘11’ and ‘010’, respectively. The label bits and information bits II enter FEC encoder. Since additional two and one uniform bits are required to combine with the label bits of symbol 0 and 1, respectively, the check bits of FEC and information bits II are used to implement the mapping with label bits. The mapping function of 49QAM is shown in Fig. 1(c). It is observed that two successive amplitudes differ in only one bit, which means Gray mapping is achieved.

The probability distribution of CCDM for other irregular QAM formats are shown in Tab. 1. The partial label and mapping function can be obtained with a similar design as shown in Fig. 1(b) and (c). It is noted that this scheme can also be used to realize arbitrary pulse amplitude modulation (PAM) formats in intensity modulation and direct detection (IMDD) systems.

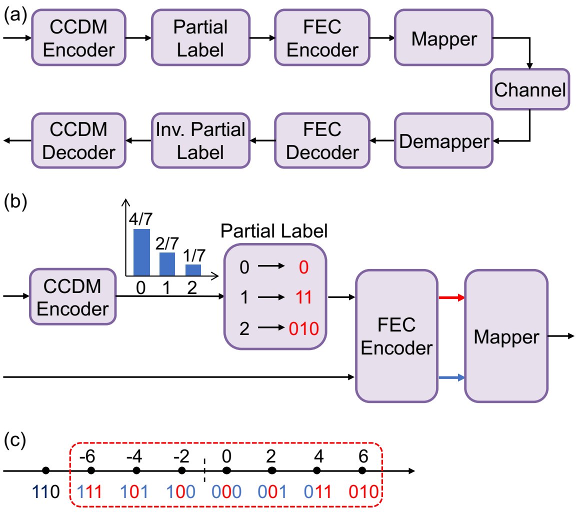

Fig. 1: (a) The block diagram of implementation for irregular QAM formats. (b) The detailed process to implement 49QAM. (c) The mapping function of 49QAM. The red bits are from label bits. The blue bits are from information bits II and check bits.

Tab. 1: The probability distributions of CCDM for irregular QAM formats.

Modulation format	Probability Distribution
9QAM	2/3, 1/3
25QAM	4/5, 1/5
36QAM	4/6, 2/6
49QAM	4/7, 2/7, 1/7
81QAM	8/9, 1/9
100QAM	8/10, 2/10
121QAM	8/11, 2/11, 1/11
144QAM	8/12, 4/12
169QAM	8/13, 4/13, 1/13
196QAM	8/14, 4/14, 2/14
225QAM	8/15, 4/15, 2/15, 1/15

Simulation Results in an AWGN Channel

Firstly, the performance of various modulation formats is compared in an additive white Gaussian noise (AWGN) channel under a peak-power constraint. Fig. 2(a) shows the results of generalized mutual information (GMI) versus peak-signal-to-noise ratio (PSNR) for different transmitted signals. Signals shaped via CCDM with the same entropies as irregular QAM signals are also included for comparison. The adopted block length of CCDM is 2000. As shown in Fig. 2(a), probabilistically shaped signals have worse performance since they have a larger peak-to-average power (PAPR) compared to uniform signals.

In addition, the optimal GMI of conventional 16QAM, 64QAM and 256QAM is compared to that of all uniform signals and the results are shown in Fig. 2(b). Compared to conventional QAM signals, irregular QAM signals achieve PSNR gains of 0.3 dB and 0.15 dB at a GMI of 4 bits/2D-symbol with block lengths of 2000 and 200, respectively.

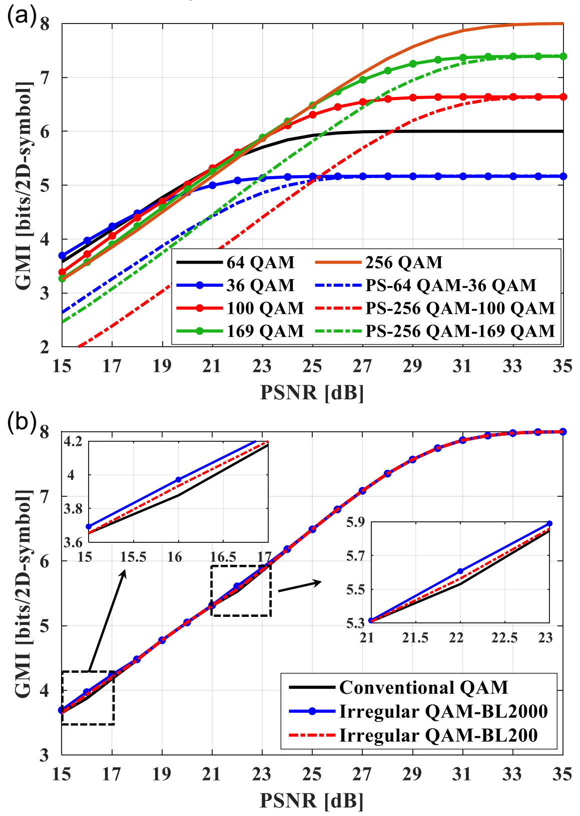

Fig. 2: Simulation results over an AWGN channel with a peak power constraint. (a) GMI for various modulation formats. CCDM is implemented with a block length of 2000. (b) Optimal GMI for conventional and irregular QAM formats.

Results with Transceiver Impairments

The performance of conventional and irregular QAM formats is also compared in optical coherent systems with transceiver impairments. The simulation setup is depicted in Fig. 3. In the transmitter, the transmitted signals of various QAM formats are generated and the symbol rates are adjusted according to net bit rates. A root-raised-cosine (RRC) filter with a roll-off factor of 0.1 is adopted for pulse shaping. A pilot tone is inserted into the signal with a frequency gap of 1 GHz. Afterwards, digital pre-distortion is used to compensate the nonlinearity from I/Q modulators. In digital-to-analog converters (DACs), the number of quantization bits is 7 and the clipping ratio is optimized for different modulation formats. Besides, a Chebyshev type-I low pass filter with a 3-dB bandwidth of 36 GHz or 50 GHz and a passband ripple less than 0.75 dB is employed to emulate the transmitter bandwidth limitation. After four radio frequency (RF) drivers, two I/Q modulators with a modulation depth of 50% are used. The adopted laser has a power of 14 dBm and a linewidth of 100 kHz.

At the receiver, the signal is detected by a coherent receiver which consists of two optical hybrids and four balanced photodiodes (BPDs). The responsivity and dark current of each photodiode are set as 0.8 A/W and 5×10^{-9} A, respectively. The power spectral density of thermal noise is 14×10^{-12} A/Hz$^{1/2}$. A local oscillator (LO) with a power of 12 dBm and a linewidth of 100 kHz is used. A same Chebyshev type-I filter is used to emulate the receiver bandwidth limitation. After the transimpedance amplifiers (TIAs), the four signals are quantized by the analog-to-digital converters (ADCs) with 7 quantization bits and 7-dB clipping ratio. The digital signal processing (DSP) includes pilot-tone-aided carrier phase recovery (CPR), matched filtering and decision-directed least-mean square (DD-LMS) equalization. Finally, normalized generalized mutual information (NGMI) is calculated [13, 14].

The results of power budget versus net bit rate are shown in Fig. 4. The link budget is calculated by the difference between the launch power and the required received optical power (ROP) at an NGMI threshold of 0.78, which is based on the non-ideal FEC with a code rate of 3/4 [13].

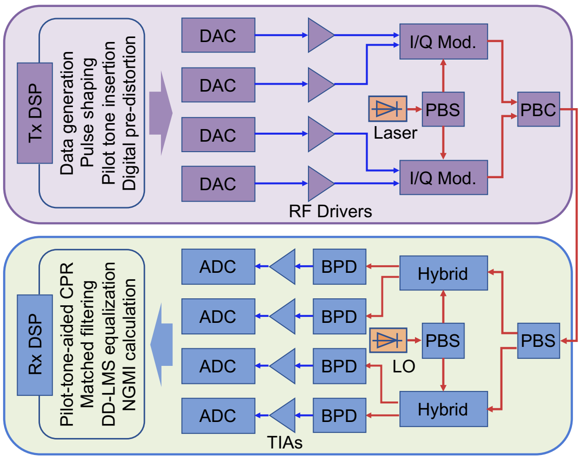

Fig. 3: Simulation setup. PBS: polarization beam splitter; PBC: polarization beam combiner.

Fig. 4(a) and (b) show the results with 3-dB bandwidths of 50 GHz and 36 GHz, respectively. As shown in Fig. 4(a), for low data rates, the bandwidth limitations for all modulation formats are small. Thus, lower order modulation formats provide a better performance due to the larger tolerance to noise. As the net bit rate increases, low order modulation formats suffer from severe bandwidth limitations, leading to a significant performance degradation. The proposed irregular QAM formats are able to achieve a better adaptation between signal entropy and symbol rate of the underlying systems. Compared with 64QAM, 36QAM achieves 2.32 dB gain of power budget at a net bit rate of 650 Gbit/s. Besides, 49QAM achieves 1.82 dB and 1.9 dB gains of power budget over 64QAM at net bit rates of 700 and 750 Gbit/s, respectively.

The similar results are shown in Fig. 4(b) with a more severe bandwidth limitation. To realize the same data rate with a narrower bandwidth, higher order modulation formats with higher spectral efficiencies are required. Since high order modulation formats are less tolerable to noise, smaller power budgets are obtained. The results show that compared to 256QAM, 144QAM achieves 1.86 gain of power budget at the bit rates of 700 Gbit/s.

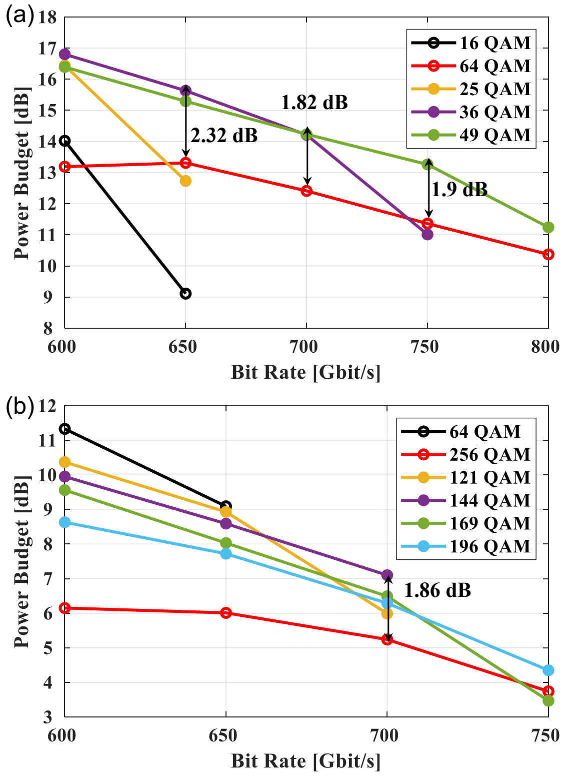

Fig. 4: Simulation results of power budget versus net bit rate with a 3-dB bandwidth of (a) 50 GHz, and (b) 36 GHz.

Conclusion

In this paper, we propose a low-complexity scheme to realize arbitrary M^2-ary QAM formats with Gray mapping in short-reach amplifier-less coherent optical systems. The proposed irregular QAM formats enable a better adaptation between signal entropy and symbol rate of the underlying systems. The performance is demonstrated by simulations. It is shown 36QAM and 49QAM achieve 2.32 dB and 1.9 dB gains of power budget over 64QAM at net bit rates of 650 Gbit/s and 750 Gbit/s, respectively.

Acknowledgements

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References

[1] X. Zhou, R. Urata, and H. Liu, “Beyond 1 Tb/s intra-data center interconnect technology: IM-DD or coherent?,” *J. Lightw. Technol.*, vol. 38, no. 2, pp. 475–484, Jan. 2020.

[2] R. Nagarajan, I. Lyubomirsky, and O. Agazzi, “Low power DSP-based transceivers for data center optical fiber communications (Invited Tutorial),” *J. Lightw. Technol.*, vol. 39, no. 16, pp. 5221–5231, Aug. 2021.

[3] F. Buchali, M. Chagnon, K. Schuh, P. Dong, and H. Buelow, “Amplifier less 400 Gb/s coherent transmission at short reach,” in *Proc. Eur. Conf. Opt. Commun.,* 2018, Paper PDP.3.4.

[4] B. M. Oliveira, F. P. Guiomar, M. C. R. Medeiros, and P. P. Monteiro, “Enhancing power budget and spectral efficiency in amplifier-less coherent optical links,” *IEEE Photon. Technol. Lett.*, vol. 33, no. 24, pp. 1383–1386, Dec. 2021.

[5] G. Böcherer, F. Steiner, and P. Schulte, “Bandwidth efficient and rate-matched low-density parity-check coded modulation,” *IEEE Trans. Commun.*, vol. 63, no. 12, pp. 4651–4665, Dec. 2015.

[6] G. Böcherer, P. Schulte, and F. Steiner, “Probabilistic shaping and forward error correction for fiber-optic communication systems,” *J. Lightw. Technol.*, vol. 37, no. 2, pp. 230–244, Jan. 2019.

[7] J. Cho and P. J. Winzer, “Probabilistic constellation shaping for optical fiber communications,” *J. Lightw. Technol.*, vol. 37, no. 6, pp. 1590–1607, Mar. 2019.

[8] M. Fu, Q.Liu, H. Lun, H. Jiang, Y. Wu, X. Liu, Z. Yang, L. Yi, W. Hu, and Q. Zhuge, “Parallel bisection-based distribution matching for nonlinearity-tolerant probabilistic shaping in coherent optical communication systems,” *J. Lightw. Technol.*, vol. 39, no. 20, pp. 6459–6469, Oct. 2021.

[9] M. Fu, Q. Liu, Y. Xu, H. Jiang, X. Zeng, Y. Wu, L. Yi, W. Hu, and Q. Zhuge, “Multi-dimensional distribution matching with bit-level shaping for probabilistically shaped high order modulation formats,” *J. Lightw. Technol.*, vol. 40, no. 9, pp. 2870–2879, May 2022.

[10] D. Che, J. Cho, and X. Chen, “Does probabilistic constellation shaping benefit IM-DD systems without optical amplifiers?,” *J. Lightw. Technol.*, vol. 39, no. 15, pp. 4997–5007, Aug. 2021.

[11] B. Oliveira, A. Lorences-Riesgo, F. Guiomar, M. Medeiros, and P. Monteiro, “Optimizing probabilistic constellation shaping for amplifier-less coherent optical links,” *J. Lightw. Technol.*, vol. 39, no. 13, pp. 4318–4330, Jul. 2021.

[12] P. Schulte and G. Böcherer, “Constant composition distribution matching,” *IEEE Trans. Inf. Theory*, vol. 62, no. 1, pp. 430–434, Jan. 2016.

[13] A. Alvarado, E. Agrell, D. Lavery, R. Maher, and P. Bayvel, “Replacing the soft-decision FEC limit paradigm in the design of optical communication systems*,” *J. Lightw. Technol.*, vol. 34, no. 2, pp. 707–721, Jan. 2016.

[14] J. Cho, L. Schmalen, and P. J. Winzer, “Normalized generalized mutual information as a forward error correction threshold for probabilistically shaped QAM,” in *Proc. Eur. Conf. Opt. Commun.*, 2017, Paper M.2.D.2.