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Abstract: We compare various modulation formats and variable-rate LDPC codes based on required GMI in nonlinear fiber transmissions. Pareto-efficient pairs of modulation and coding are identified to achieve both higher spectral efficiency and higher nonlinearity tolerance.

OCIS codes: (060.4510) Optical communications, (060.1660) Coherent communications, (060.4080) Modulation.

1. Introduction

Generalized mutual information (GMI) has been recently used to predict soft-decision decoding performance for bit-interleaved coded modulation (BICM) systems using various modulation formats [1–3]. In [3], the optimal set of modulation order and code rate was experimentally identified. It was found that some pairs of high-order quadrature-amplitude modulation (QAM) and low-rate forward-error correction (FEC) code provide higher spectral efficiency (SE); for example, low-rate 16QAM having an FEC overhead (OH) of 194% can outperform high-rate 4QAM. Although GMI analysis is more accurate than classical pre-FEC bit-error rate (BER) or required signal-to-noise ratio (SNR), the GMI itself does not guarantee the existence of practical FEC codes achieving the target code rate. In fact, hardware-implementable state-of-the-art low-density parity-check (LDPC) codes [4–6] still have $0.5 \sim 1.5$ dB penalty from the BICM capacity because of implementation limitations such as power consumption and memory size. In addition, it was shown in [6] that lower-rate LDPC codes usually require more decoding iterations to converge. It is also expected that higher-order QAMs are more susceptible to fiber nonlinearity and phase noise. In order to improve performance, high-dimensional modulation (HDM) formats [7–12], such as polarization-switched quadrature phase-shift keying (PS-QPSK) and set-partitioned (SP) QAM, have received a lot of interest in recent years. For example, 4-dimensional (4D) 2-ary amplitude 8-ary PSK (4D-2A8PSK) [11] and 8D-X constellation [12] have shown reduced fiber nonlinearity, especially for dispersion-managed (DM) fiber plants.

This paper aims at evaluating nonlinear transmission performance of various modulation formats (not only regular QAMs but also some HDMs) with a restricted set of realistic LDPC codes (from low to high code rates), so that we can identify the best modulation and coding pairs. We show some best pairs of modulation and coding in the sense of Pareto efficiency, where higher SE and higher nonlinearity resilience can be achieved at the same time.

2. Adaptive Modulation and Coding (AMC) Set

We consider ten different modulation formats (for $2 \sim 6$ bits per symbol) and three different code rates of state-of-the-art LDPC codes, as listed in Table 1. In addition to regular QAMs such as dual-polarization (DP) 16QAM, we compare various HDMs including SP-128QAM, 4D-2A8PSK [11], and 8D-X [12]. We use iteration-aware Pareto-optimal LDPC codes recently proposed in [6], which maximizes a net coding gain (NCG) and minimizes the power consumption at the same time for practical applications. The high-rate LDPC code in Table 1 achieves an NCG of 12.0 dB, which is comparable to the one of the world-best practical LDPC codes reported in [4]. While achieving high NCG, this Pareto-optimal code can significantly reduce the power consumption by 66% from the code in [4]. All the LDPC codes in Table 1 consume approximately identical power for decoding. The NCG of 12.0 dB corresponds to a required SNR of 5.0 dB, at which the BICM systems provide a GMI of 0.860.

Fig. 1 shows the code rate as a function of required SNR of those LDPC codes for DP-QPSK. It is shown in Fig. 1 that those recently developed LDPC codes still have approximately 1 dB loss from the idealistic BICM capacity because of the hardware limitation of power consumption, and also that lower-rate LDPC codes have higher penalty (i.e., 1.16, 1.04, and 0.90 dB for low-/mid-/high-rate LDPC codes). Although the required SNR can change for different modulations, the corresponding required GMI (RGMI) is universally applicable to any arbitrary modulation formats in

BICM systems. Due to the penalty of practical LDPC codes, the real code rate (i.e., $0.8, 0.65, 0.5$) can be significantly lower than the RGMI (i.e., $0.860, 0.732, 0.588$), in particular for low-rate regimes. This suggests that idealistic GMI analysis without taking account of such a rate loss can be too optimistic to evaluate SE. In this paper, we consider realistic LDPC codes with rate loss to optimize the pair of modulation formats and variable-rate LDPC codes through the analysis of RGMI in nonlinear fiber transmissions.

Table 1: Modulation and Coding Set

b/sym.	2D	4D	8D
2	DP-BPSK		8D-X
3		PS-QPSK	
4	DP-QPSK		
5		SP-32QAM	
6	DP-8QAM, 8PSK	4D-2A8PSK	
7		SP-128QAM	
8	DP-16QAM		

LDPC	Rate	OH	NCG	RGMI
High rate	0.80	25.0%	12.0 dB	0.860
Mid rate	0.65	53.8%	13.0 dB	0.732
Low rate	0.50	100%	13.6 dB	0.588

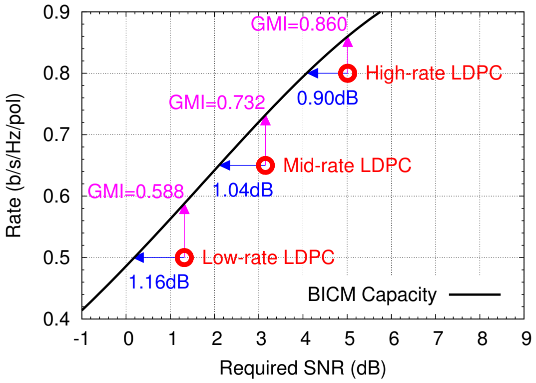

Fig. 1: Rate vs. SNR.

Table 2: Fiber Plants

Link	DM	UC
Fiber type	NZDSF	SSMF
D ps/nm/km	3.9	17
γ /W/km	1.6	1.2
α dB/km	0.2	0.2
CD inline comp.	90%	0%
CD pre-comp.	50%	50%
Span length	80 km	80 km
Number of spans	25	25
EDFA NF	5 dB	5 dB

3. Nonlinear Fiber-Optic Transmission

We evaluate nonlinear transmission performance over two types of fiber links of 2000 km; a DM link of non-zero dispersion shifted fiber (NZDSF) and a dispersion un-compensated (UC) link of standard single-mode fiber (SSMF), to investigate the effect of high and low fiber nonlinearity, respectively. Table 2 shows some parameters for the DM and UC links. The transmitter uses a root-raised-cosine (RRC) filter with a roll-off factor of 0.1. Five channels were simulated with 37.5 GHz spacing for 34.0 GBaud with no optical filtering. We used the Manakov model for the nonlinear fiber simulation. Other fiber effects such as dispersion slope and polarization mode dispersion were not simulated. For the DM link, at the end of each span, 90% of the chromatic dispersion (CD) was compensated as an ideal lumped inline compensator. The transmitter employed 50% residual CD pre-compensation for both the DM and UC links. An ideal homodyne coherent receiver was used, with the RRC filter of a roll-off factor of 0.1, followed by sampling at twice the symbol rate. Ideal CD equalization and 15-tap data-aided least-mean-square equalization were employed. Assuming that the span loss was compensated by Erbium-doped fiber amplifier (EDFAs) with a noise figure (NF) of 5.0 dB, the corresponding optical noise is loaded just before the receiver. Span loss budget [13] (i.e., link margin from required optical SNR for a target GMI) was used as a performance metric of nonlinearity resilience.

4. Performance Results

The plots of span loss budget vs. launch power for various modulation formats are shown in Figs. 2 and 3 for high-rate coding in DM link and low-rate coding in UC link, respectively, as examples. It is observed that the optimal launch power achieving the maximum budget depends on different pair of modulation and coding as well as fiber plants. We use the maximum of span loss budget across the launch power as a figure of merit. In the presence of higher nonlinearity in the DM link, 4D-2A8PSK and 8D-X offer significant advantage over 2D modulations. However, this performance gain highly depends on fiber plants and code rates. For example, for low-rate coding in the UC link, those HDM formats can be worse than 2D modulations as shown in Fig. 3.

We then plot the achievable SE vs. maximum span loss budget for all the pairs of modulation and coding in Figs. 4 and 5 for the DM and UC links, respectively. In order to select the best pairs of modulation and coding, we introduce the concept of Pareto efficiency, in which both the SE and the span loss budget are maximized at the same time. For example, SP-32QAM is Pareto inefficient because there exists other pairs of modulation and coding, which achieve both higher SE and higher span loss budget.

We summarize the results of Pareto-optimal set in Tables 3 and 4, which list the achievable SE only when the pair of modulation and coding is Pareto efficient, respectively, for the DM and UC fiber plants. It should be noticed that HDMs are not always efficient for different code rates; for example, 4D-2A8PSK outperforms DP-8QAM and DP-8PSK except for low-rate coding. Interestingly, DP-8PSK can be optimal when combined with low-rate LDPC code irrespective of fiber plants. For another example, low-rate DP-BPSK can be better than 8D-X in the UC link. It is

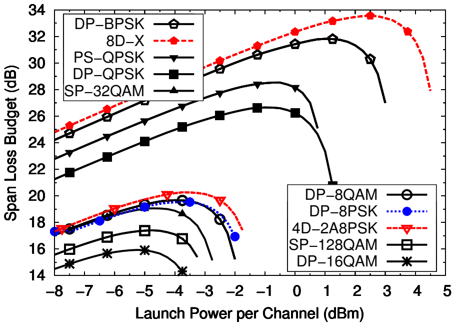

Fig. 2: Span loss budget (high-rate DM).

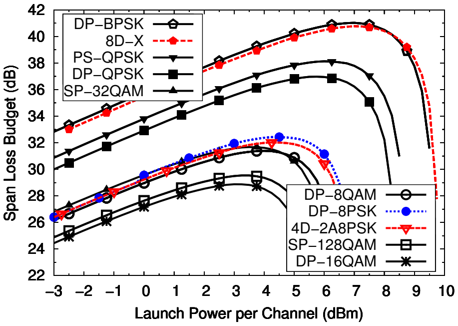

Fig. 3: Span loss budget (low-rate UC).

Table 3: Optimal Set (DM)

Modulation	SE (b/s/Hz)		
	High	Mid	Low
DP-16QAM	6.4	5.2	4.0
SP-128QAM	5.6	—	—
4D-2A8PSK	4.8	—	—
DP-8QAM	—	—	—
DP-8PSK	—	3.9	3.0
SP-32QAM	—	—	—
DP-QPSK	3.2	2.6	2.0
PS-QPSK	—	—	—
8D-X	1.6	1.3	1.0
DP-BPSK	—	—	—

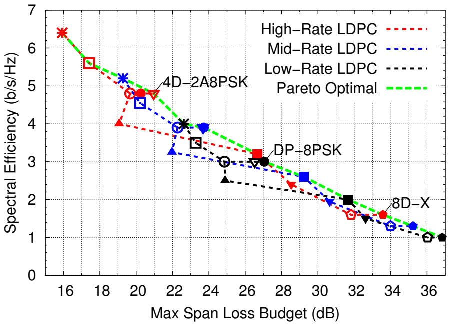

Fig. 4: SE vs. max. budget (DM).

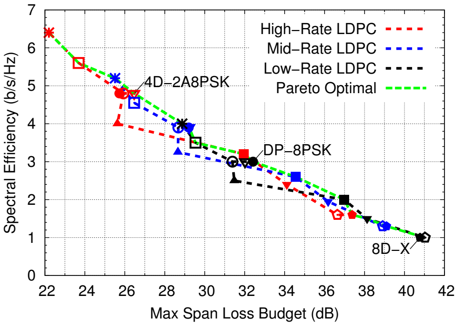

Fig. 5: SE vs. max. budget (UC).

Table 4: Optimal Set (UC)

Modulation	SE (b/s/Hz)		
	High	Mid	Low
DP-16QAM	6.4	5.2	4.0
SP-128QAM	5.6	—	3.5
4D-2A8PSK	4.8	3.9	—
DP-8QAM	—	—	—
DP-8PSK	—	—	3.0
SP-32QAM	—	—	—
DP-QPSK	3.2	2.6	2.0
PS-QPSK	—	—	1.5
8D-X	1.6	1.3	—
DP-BPSK	—	—	1.0

found that regular DP-16QAM and DP-QPSK are Pareto efficient irrespective of three code rates and two fiber plants. Some HDMs can be Pareto efficient when the code rate is high irrespective of fiber plants.

5. Conclusions

We analyzed GMI of various modulation formats including HDM in nonlinear fiber transmissions. To consider realistic variable-rate LDPC codes, we take the code rate loss into account for GMI analysis. We identified Pareto-efficient pairs of modulation and coding to maximize the SE and span loss budget at the same time. It was found that low-rate DP-8PSK can be Pareto efficient, whereas some HDMs such as 4D-2A8PSK and 8D-X can be inefficient when combined with low-rate LDPC codes.

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References

1. A. Alvarado and E. Agrell, “Four-dimensional coded modulation with bit-wise decoders for future optical communications,” *JLT* **33** 10 (2015), pp. 1993–2003.
2. R. Rios-Mueller, J. Renaudier, L. Schmalen, and G. Gharlet, “Joint coding rate and modulation format optimization for 8QAM constellations using BICM mutual information,” in *OFC* (2015), paper W3K.4.
3. R. Maher, A. Alvarado, D. Lavery, and P. Bayvel, “Modulation order and code rate optimisation for coherent transceivers using generalized mutual information,” in *ECOC* (2015), paper Mo.3.3.4.
4. K. Sugihara, Y. Miyata, T. Sugihara, K. Kubo, H. Yoshida, W. Matsumoto, and T. Mizuochi, “A spatially-coupled type LDPC code with an NCG of 12 dB for optical transmission beyond 100 Gb/s,” in *OFC* (2013), paper OM2B.4.
5. I. B. Djordjevic, “Advanced coded-modulation for ultra-high-speed optical transmission,” in *OFC* (2014), paper W3J-4.
6. T. Koike-Akino, D. S. Millar, K. Kojima, K. Parsons, Y. Miyata, K. Sugihara, and W. Matsumoto, “Iteration-aware LDPC code design for low-power optical communications,” *JLT* **33** 24 (2015).
7. E. Agrell and M. Karlsson, “Power-efficient modulation formats in coherent transmission systems,” *JLT* **27** (2009), pp. 5115–5126.
8. L. Beygi, E. Agrell, J. M. Kahn, and M. Karlsson, “Rate-adaptive coded modulation for fiber-optic communications,” *JLT* **32** 2 (2014), pp. 333–343.
9. T. Liu and I. B. Djordjevic, “Multidimensional Optimal Signal Constellation Sets and Symbol Mappings for Block-Interleaved Coded-Modulation Enabling Ultrahigh-Speed Optical Transport,” *IEEE Photon. J.* **6** 4 (2014).
10. D. S. Millar, T. Koike-Akino, S. Ö. Arık, K. Kojima, K. Parsons, T. Yoshida, and T. Sugihara, “High-dimensional modulation for coherent optical communications systems,” *Opt. Exp.* **22** 7 (2014), pp. 8798–8812.
11. K. Kojima, D. S. Millar, T. Koike-Akino, and K. Parsons, “Constant modulus 4D optimized constellation alternative for DP-8QAM,” in *ECOC* (2014), paper P.3.25.
12. A. D. Shiner, M. Reimer, A. Borowiec, S. Oveis Gharan, J. Gaudette, P. Mehta, D. Charlton, K. Roberts, and M. O’Sullivan, “Demonstration of an 8-dimensional modulation format with reduced inter-channel nonlinearities in a polarization multiplexed coherent system,” *Opt. Exp.* **22** 17 (2014), pp. 20366–20374.
13. P. Poggiolini, G. Bosco, A. Carena, V. Curri, and F. Forghieri, “Performance evaluation of coherent WDM PS-QPSK (HEXA) accounting for non-linear fiber propagation effects,” *Opt. Exp.* **18** 11 (2010), pp. 11360–11371.