Experimental Demonstration of Nonbinary LDPC Convolutional Codes for DP-64QAM/256QAM

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Abstract *We show the great potential of nonbinary LDPC convolutional codes (NB-LDPC-CC) with low-latency windowed decoding. It is experimentally demonstrated that NB-LDPC-CC can offer a performance improvement of up to 5 dB compared with binary coding.*

Introduction

Recent optical communications systems have used soft-decision (SD) decoding with low-density parity-check (LDPC) codes[1–9]. Although modern LDPC codes already achieve near-capacity performance in binary additive white Gaussian noise (BiAWGN) channels, conventional bit-interleaved coded modulation (BICM) based on binary LDPC codes has a fundamental limit compared to the theoretical bound, in particular for high-order modulation. By employing BICM iterative demodulation (BICM-ID), the performance can be significantly improved[10]. However, BICM-ID requires SD feedback from the decoder to demodulator. Hence, BICM-ID can be less practical due to the high complexity and large latency. By contrast, with nonbinary (NB) LDPC codes[11–16], turbo demodulation is not needed while achieving the theoretical bound. This scheme called nonbinary-input coded modulation (NBICM)[15] offers even better performance than BICM-ID while keeping the total complexity low, especially when combined with high-order and high-dimensional modulation. This is a great advantage of NB-LDPC compared to BICM and BICM-ID. However, the major obstacle has laid in the fact that the decoder complexity increases with the Galois field (GF) size.

Recently, it was suggested[14] that the complexity issue of nonbinary decoding can be mitigated by introducing LDPC convolutional codes (LDPC-CCs)[2–9] with windowed decoding (WD). LDPC-CCs have drawn significant interest in recent years because of their theoretical features such as a saturation property and the practical feasibility of WD, which is capable of low-latency and low-memory decoding. In this paper, we experimentally demonstrate a significant performance gain provided by NB-LDPC-CC in comparison to BICM, for dual-polarization 64-ary quadrature-amplitude modulation (DP-64QAM) and DP-256QAM. As the complexity of WD is roughly proportional to the window size and the maximum column weight, we consider the minimum column weight of 2 and small window size $W = 6$ for low-power decoding.

GMI of BICM and NBICM

Generalized mutual information (GMI)[17] has been recently used to predict SD performance of various modulation formats. The GMI can be extended[16] for any nonbinary coding schemes as

$$I_{\text{GMI}} = 1 - \mathbb{E}\Big[\log_Q \sum \exp(-L_q)\Big| B = 0\Big],$$

where $\mathbb{E}[\cdot]$ denote the expectation, $\{L_0, \ldots, L_{Q-1}\}$ denote the log-likelihood ratio (LLR) vector as $L_q = \log \Pr(B = 0)/\Pr(B = q)$ for the q-th element of $\mathbb{GF}(Q)$, Q is the GF size, and B is the transmitted element. When $Q = 2$, it reduces to the conventional GMI for BICM systems. If the GF size Q matches the modulation order M, the above GMI is simply called MI for some literature as a coded modulation bound. Fig. 1 shows the normalized GMI for M-ary QAM with different GF size $Q \in \{2, 8, 16, 64, 256\}$. Although binary coding systems (BICM with $Q = 2$) have no degradation from nonbinary coding systems for high rate regimes, BICM can suffer $0.5 \sim 1.5$ dB loss in particular for higher-order modulation in mid-/low-rate regimes. In contrast, the GMI of the NBICM systems can closely approach the Shannon limit for low signal-to-noise ratio (SNR). Note that even when

$Q < M$, NBICM shows some gain over BICM.

It was experimentally demonstrated[17] that high-order QAM with low-rate code provides higher spectral efficiency; e.g., low-rate 16QAM having an overhead (OH) of 194% can be optimal. It suggests that the performance of mid-/low-rate LDPC codes is also of a great importance.

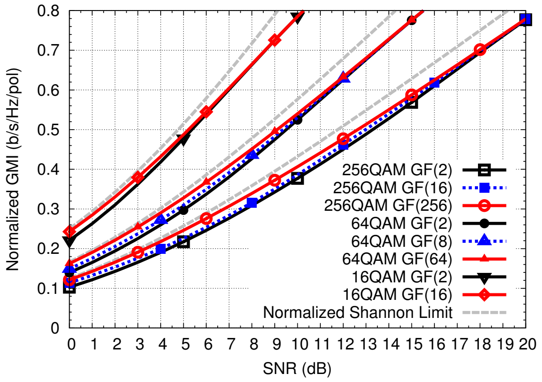

Fig. 1: Normalized GMI for 16/64/256QAMs.

In this paper, we use quasi-cyclic (QC) NB-LDPC-CCs denoted by a protograph of $(J, K, L, N)_{\mathbb{GF}(Q)}$, where J is a column weight, K is a row weight, L is a termination length, and N is a QC size. The codeword length is $38{,}400$ bits long, which is identical to a state-of-the-art LDPC code[5]. To keep the same codeword length for various GF size, the QC size is scaled by Q. More specifically, we consider two protographs $(2, 20, 20, 384/\log_2 Q)_{\mathbb{GF}(Q)}$ and $(2, 4, 50, 384/\log_2 Q)_{\mathbb{GF}(Q)}$ for the code rates of 0.79 (26.6% OH) and 0.49 (104% OH), respectively, for $Q \in \{2, 4, 8, 16, 64, 256\}$. We use low-latency WD having a limited window size of $W = 6$ and adaptive stopping criterion[15]. Such low-weight codes with small window size allows significant reduction in computational complexity and memory requirement for nonbinary decoding.

Experimental setup

NB-LDPC-CC performance was validated experimentally in a back-to-back configuration for DP-64QAM and DP-256QAM. The experimental setup[18,19] is illustrated in Fig. 2. A pair of digital-to-analog converters (DACs) operating at 20 GSa/s was used to generate 64QAM and 256QAM signals at 10 GBd, including 1% pilot symbols. These signals were filtered with a root-raised-cosine filter with a roll-off factor of 0.1%. After amplification, these signals were applied to an I/Q modulator operating in the linear regime. The optical carrier was generated by an external cavity laser (ECL), with a linewidth of 100 kHz. Polarization-multiplexing was emulated passively in the optical domain with a delay of 489 symbols. Noise loading was performed by coupling in a variable power source of amplified spontaneous emission (ASE) noise. A discrete component coherent receiver was used with a bandwidth of 70 GHz, while the local oscillator was an ECL with linewidth of 100 kHz. Quantization was performed using an oscilloscope with 63 GHz bandwidth and 160 GSa/s. Offline post-processing was then performed.

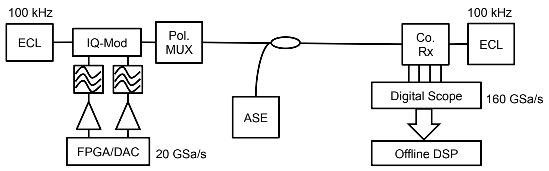

Fig. 2: Experimental setup[18,19].

Our receiver digital-signal processing consisted of conventional deskew, 4th power intradyne frequency estimation, and matched filtering. A 2×2 equalizer was used to compensate for polarization rotation, residual intersymbol interference removal and timing recovery. The equalizer was radially trained for good convergence, before being switched to pilot-aided operation. A radius directed error term was calculated based on the pilot symbols only, with updating performed using the least-mean-square algorithm and an error term averaged over 10 pilot symbols. Recently proposed carrier phase estimation[18] was then performed. We calculated LLR vectors using a clustering algorithm to account for transmitter distortion. The NB-LDPC-CC was then decoded using WD based on fast Fourier transform Q-ary sum-product algorithm.

Experimental results

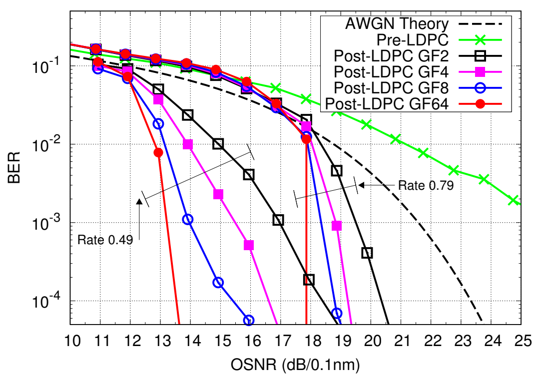

Fig. 3: Experimental results for DP-64QAM

The results of our experiments are presented in Figs. 3 and 4. Although pre-LDPC performance exhibits an error floor and a large penalty from theoretical AWGN performance, LDPC-CCs

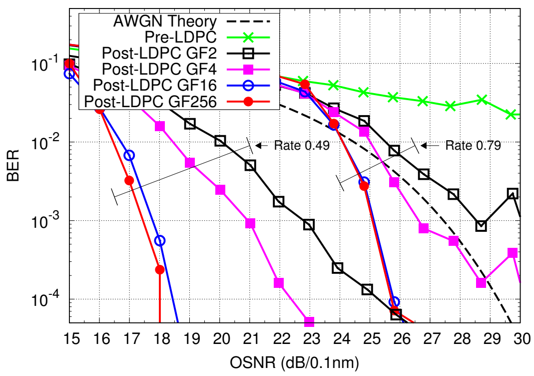

Fig. 4: Experimental results for DP-256QAM

were able to achieve error-free performance over $65{,}536$ symbols for both DP-64QAM and DP-256QAM at high SNRs. More importantly, the bit-erorr-rate (BER) performance can be significantly improved by increasing the GF size. In particular for 256QAM with low-rate code, the performance improvement by nonbinary coding is more than 5 dB gain at a BER of 10^{-3}. The reason why NB-LDPC-CCs offer more significant gains in comparison to the GMI predictions in Fig. 1 is because we considered practical WD for LDPC-CCs, using a very small window size $W = 6$ and column weight of 2 for low-power decoding.

Conclusions

We have experimentally demonstrated NB-LDPC-CC performance in back-to-back configuration using 10 GBd DP-64QAM and 256QAM, with transmitter and receiver laser linewidths of 100 kHz. Significant performance improvement by up to 5 dB gain was confirmed in the experiments. Using low-latency WD with small window size for low-weight NB-LDPC-CCs, the required computational complexity and memory size for nonbinary decoding can be maintained low, while achieving excellent BER performance.

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References

[1] I. B. Djordjevic, “Advanced coded-modulation for ultra-high-speed optical transmission,” in *OFC* (2014), paper W3J-4.

[2] S. Kudekar, T. Richardson, and R. Urbanke, “Threshold saturation via spatial coupling: Why convolutional LDPC ensembles perform so well over the BEC,” *IEEE TIT* **57** (2011), pp. 803–834.

[3] L. Schmalen, V. Aref, J. Cho, and K. Mahdaviani, “Next generation error correcting codes for lightwave systems,” in *ECOC* (2014), paper Th.1.3.3.

[4] F. Buchali, L. Schmalen, A. Klekamp, K. Schuh, and A. Leven, “5 × 50 Gb/s WDM Transmission of 32 Gbaud DP-3-PSK over 36,000 km fiber with spatially coupled LDPC coding,” in *OFC* (2014), paper W1A-1.

[5] K. Sugihara et al., “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.

[6] A. Leven and L. Schmalen, “Status and recent advances on forward error correction technologies for lightwave systems,” *JLT* **32** 16 (2014), pp. 2735–2750.

[7] L. Schmalen, D. Suikat, D. Rosener, and A. Leven, “Evaluation of left-terminated spatially coupled LDPC codes for optical communications,” in *ECOC* (2014), paper Th.2.3.4.

[8] D. Chang et al., “LDPC convolutional codes using layered decoding algorithm for high speed coherent optical transmission,” in *OFC* (2014), paper OW1H.4.

[9] T. Xia et al., “Dynamic window decoding for LDPC convolutional codes in low-latency optical communications,” in *OFC* (2015), paper Th3E.4.

[10] T. Koike-Akino, D. S. Millar, K. Kojima, and K. Parsons, ”Coded modulation design for finite-iteration decoding and high-dimensional modulation,” in *OFC* (2015), paper W4K.1.

[11] D. Declercq and M. Fossorier, “Decoding algorithms for nonbinary LDPC codes over GF,” *IEEE TCOMM* **55** 4 (2007), pp. 633–643.

[12] M. Arabaci, I. B. Djordjevic, R. Saunders, and R. M. Marcoccia, “High-rate nonbinary regular quasi-cyclic LDPC codes for optical communications,” *JLT* **27** 23 (2009), pp. 5261–5267.

[13] I. Djordjevic and B. Vasic, “Nonbinary LDPC codes for optical communication systems,” *IEEE PTL* **17** (2005), pp. 2224–2226.

[14] L. Wei, T. Koike-Akino, D. G. Mitchell, T. E. Fuja, and D. J. Costello, “Threshold analysis of non-binary spatially-coupled LDPC codes with windowed decoding,” in *ISIT* (2014), pp 881–885.

[15] T. Xia et al., “Nonbinary LDPC convolutional codes for high-dimensional modulations,” in *SPPCom* (2015), paper SpS3D-5.

[16] L. Schmalen, A. Alvarado, and R. Rios-Muller, “Predicting the performance of nonbinary forward error correction in optical transmission experiments,” in *OFC* (2016), paper M2.A2.

[17] 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.

[18] M. Pajovic et al., “Experimental demonstration of multi-pilot aided carrier phase estimation for DP-64QAM and DP-256QAM,” in *ECOC* (2015), paper Mo.4.3.3.

[19] D. S. Millar et al., “Design of a 1 Tb/s Superchannel Coherent Receiver,” *JLT* **34** 6 (2016), pp. 1453–1463.