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

Koike-Akino, T.; Sugihara, K.; Millar, D.S.; Pajovic, M.; Matsumoto, W.; Maher, R.; Lavery, D.; Abad, A.; Paskov, M.; Kojima, K.; Parsons, K.; Thomsen, B.C.; Savory, S.J.; Bayvel, P.

TR2016-125 September 2016

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

European Conference on Optical Communication (ECOC)

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

Toshiaki Koike-Akino[1], Kenya Sugihara[2], David S. Millar[1], Milutin Pajovic[1], Wataru Matsumoto[2],
Alex Alvarado[3], Robert Maher[3], Domaniç Lavery[3], Milen Paskov[3], Keisuke Kojima[1],
Kieran Parsons[1], Benn C. Thomsen[3], Seb J. Savory[4], Polina Bayvel[3]

[1] Mitsubishi Electric Research Laboratories (MERL), Cambridge, MA 02139, USA. koike@merl.com
[2] Information Technology R&D Center, Mitsubishi Electric Corp., Ofuna, Kanagawa 247-8501, Japan
[3] Optical Networks Group, University College London (UCL), Torrington Place, London, WC1E 7JE, UK
[4] University of Cambridge, Dept. of Engineering, 9 JJ Thomson Avenue, Cambridge, CB3 0FA, UK

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 normalized GMI can be extended[14] for any nonbinary coding as

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

where $\mathbb{E}[\cdot]$ denote the expectation, $\{L_0, \dots, L_{Q-1}\}$ 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. Although binary coding systems (BICM with $Q = 2$) have little degradation from nonbinary coding systems for high rate regimes, BICM can suffer more than 0.5 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.

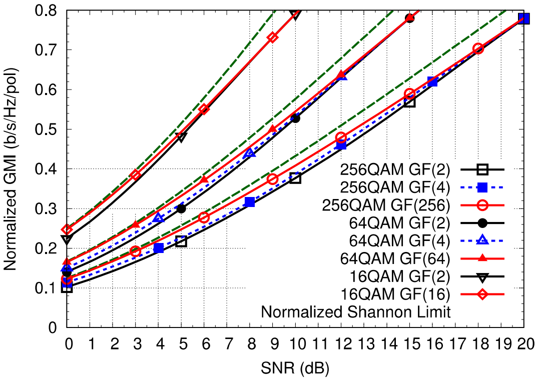

Fig. 1: Normalized GMI for 16/64/256QAMs.

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.

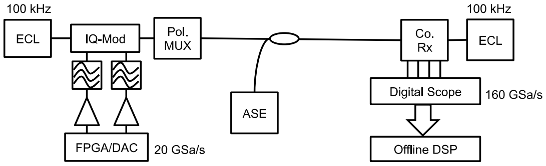

Fig. 2: Experimental setup[18,19].

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

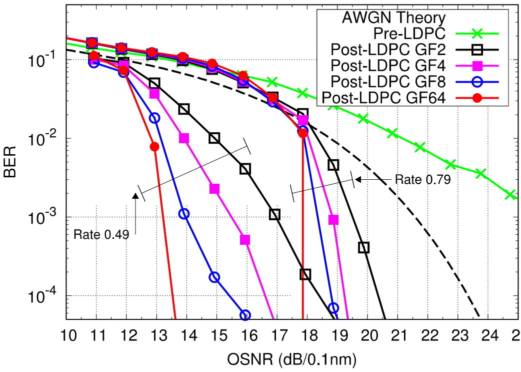

Fig. 3: Experimental results for DP-64QAM

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

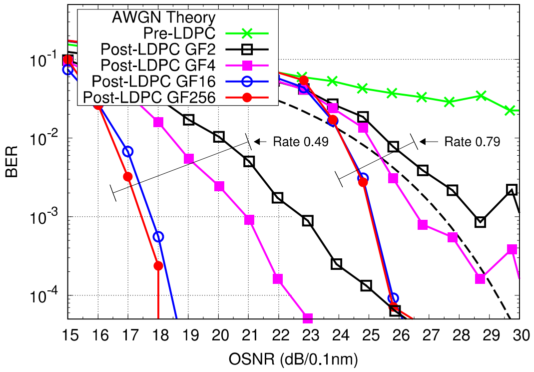

Fig. 4: Experimental results for DP-256QAM

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.

Acknowledgements

This work was in part funded by the UK EPSRC Programme Grant EP/J017582/1, and the Royal Academy of Engineering/ the Leverhulme Trust Senior Research Fellowship held by SJS.

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.