Soft Coded Modulation for Sensitivity Enhancement of Coherent 100-Gbit/s Transmission Systems

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Abstract: *Soft-decoding of a PDM-QPSK signal with 34%-FEC overhead – enabled by a symbol rate increase from 28 to 35 Gbaud – leads to 10.7-dB OSNR sensitivity. Soft-decoding is not effective for POL-QAM 6-4 modulation.*

OCIS codes: : (060.2330) Fiber optics communications, (060.4080) Modulation

1. Introduction

Today's envisaged solutions of 100-Gbit/s transmission systems are mainly based on polarization division multiplexed optical quaternary phase shift keying modulation (PDM-QPSK), coherent detection, and digital signal processing (DSP) after analog-to-digital conversion (ADC) [1-3]. Commonly it is assumed that in the bit-rate of 112-Gbit/s (28-Gbaud symbol rate) a FEC overhead of 7% is already included. Recently, the improvement of the sensitivity by soft-FEC was numerically analyzed using a large girth LDPC code [4]. The error-correction of soft-FEC is based on the use of analog signal samples rather than already decided bits. It has the potential of improving the sensitivity up to nearly 2 dB for a sufficiently high FEC overhead [5]. On the other hand, this means an increase of signal bandwidth due to a higher symbol rate.

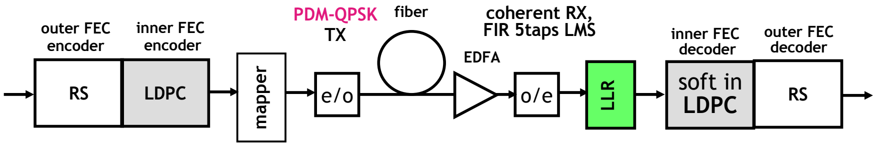
In the following work we numerically calculate the trade-off between sensitivity improvement and bandwidth enhancement of a PDM-QPSK system when applying a concatenated coding scheme consisting of soft LDPC error correction and outer Reed-Solomon (RS) coding. The performance difference between low complexity and high complexity realization will be illustrated by quantifying the improvement for low (4) and high (24) iteration count in the soft-LDPC decoder. Moreover, the sensitivity of an alternative modulation scheme (polarization QAM, POL-QAM 6-4 [6]) is reported with a more complex constellation carrying 4.5 bit/symbol rather than 4 bits/symbol (PDM-QPSK).

2. Soft-detection scheme for PDM-QPSK modulation

The considered PDM-QPSK transmission system with coherent detection is sketched out in Fig 1. At the transmitter side the successive clusters of 4 bits provided by an LDPC encoder are mapped to X and Y polarized QPSK constellations, which are modulated by a nested I-Q-modulator (o/e). After transmission and noise loading, in the receiver optimum coherent detection is assumed which provides real and imaginary part of noisy signal samples in X and Y polarization. An least-mean-square adapted 5-tap FIR butterfly filter was assumed and a low pass filter of 70% of the symbol rate. For FEC we use a concatenated coding scheme [5,7,8] as shown in Fig. 1. It consists of an LDPC and a RS code. The symbol rate is increased in order to transport the FEC overhead of the LDPC and RS. As commonly assumed, with 7% FEC overhead the bitrate becomes 112 Gbit/s corresponding to a symbol rate of 28 Gbaud.

In the receiver the log-likelihood-ratios for each bit (LLR, probability of "0" / probability of 1") are calculated from the received signal samples of a symbol [9]. The LDPC decoder applies soft signal processing, based on the LLR. The sum product algorithm (SPA) is used for decoding. The RS decoding is performed on symbol basis after quantizing the LLRs to binary values. The LDPC decoding is implemented either with 24 iterations to come close to the theoretical performance bound of the code or with 4 iterations, which represents a trade-off between implementation complexity and decoder performance. The RS code is applied in order to remove residual bit errors at the LDPC decoder output that occur either because of an LDPC code error floor in the 24 iteration case or because of the weaker decoding capabilities of the SPA decoder in the 4 iteration case. Five LDPC codes with overheads between 6.7% and 33.3% are applied. The RS codes are chosen for each LDPC code exclusively and enable a BER reduction of 10^{-6} to the final BER of 10^{-15}, as it is necessary for optical telecommunication application. This means, that the concatenated coding scheme is able to achieve error free data transmission,

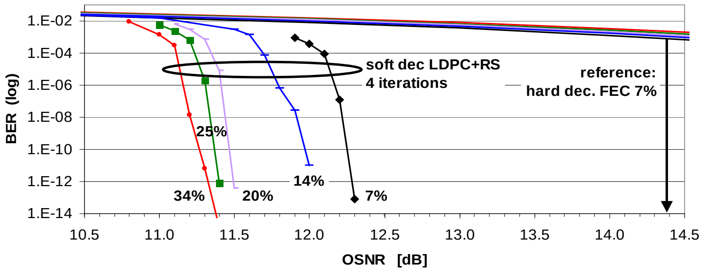
Fig. 1 Coded modulation scheme with inner LDPC code and outer Reed-Solomon code.



if the LDPC decoder is able to reduce the preFEC-BER to a BER of 10^{-6}. Since the applied LDPC codes are of cycle length 6, the error floor in the 24 iteration case will be below this value [5] and for the 4 iteration case the OSNR can be increased to achieve the 10^{-6}. One major benefit of the concatenated coding scheme is that LDPC codes can be used, that are optimized in performance (i.e. an early turbo cliff) and for high data throughput hardware implementations, without paying attention to large girth length or to any other code property. Error free transmission can be achieved even so.

The applied LDPC codes are quasi cyclic Euclidean geometry (EG) codes of type 1 and 2 [10]. The codes can be encoded by shift register encoders and exhibit a low encoding complexity. The following codes are applied. An EG LDPC code of type 1 with parameters m=2 and s=6. The parity check matrix of this code is 16 times column extended. The codeword length is N_{LDPC}=65520 bits and the information word length is K_{LDPC}=61425 bits. This LDPC code is concatenated with a shortened RS code of codeword length N_{RS}=4725 symbols and information word length K_{RS}=4713 symbols. The code concatenation has an overall overhead of $O_{c,overall}$ = 6.95%. It is referred to as LDPC(65520,61425) + RS(4725,4713). Further the EG LDPC code LDPC(4088,3577) of type 2 with m=3 and s=3 and 8 sub matrices is concatenated to the Reed Solomon code RS(398,390), the overhead is $O_{c,overall}$ = 16.63%. Besides these two code concatenations, the concatenation of LDPC(24570,20475) and RS(1862,1852) with $O_{c,overall}$ = 20.65%, the concatenation of LDPC(20475,16380) and RS(1490,1480) with $O_{c,overall}$ = 25.85% and the concatenation of LDPC(16380,12285) and RS(1117,1109) with $O_{c,overall}$ = 34.3% are applied. The three last LDPC codes are EG type 2 codes with parameters m=4 and s=3. 6, 5 and 4 sub matrices are applied to obtain the parity check matrices of the codes, respectively. In the figures the codes overheads of 6.95%, 16.63%, 20.65%, 25.85% and 34.3% are labeled by 7%, 14%, 20%, 25%, and 34%, respectively.

Fig. 2 BER vs. OSNR for LDPC coded PDM-QPSK (112 Gb/s includes 7% FEC overhead). The percent values quantify the LDPC overhead. Left solid curves: Soft-decision w. 7% to 34% overhead; Right solid curves: pre-FEC BER; Arrow from 7% curve at BER = 10^{-3} points at sensitivity of standard hard-decision FEC with 7% overhead.



Simulated pre-FEC (right curves) and post-FEC BER (left curves) for 7% to 34% LDPC+RS are shown in Fig. 2. With increasing FEC overhead, the sensitivity slightly degrades due to the increased symbol rate (right curves). Arrow from the 10^{-3} pre-FEC BER of the LDPC+RS 7% curve points at the OSNR of 14.4 dB that is commonly corrected by a standard hard-decision FEC with 7% overhead. It serves as reference. The extrapolated crossing of the left hand post-FEC curves with 10^{-16} indicate sensitivity for error-free operation between 12.4 dB (7%) and 11.4 dB (34%).

3. OSNR sensitivity

Fig. 3 illustrates the relation between the OSNR for error-free operation and relative symbol rate. The symbol rate corresponds to the required bandwidth increase. The FEC overhead of LDPC+RS appears as label at the curves. The values for 4 iterations (dashed line) have been extracted from Fig. 2. The solid line belongs to the OSNRs for 24 iterations. The LPDC 14% code was not shown due to high error floor. 24 iterations lead to a sensitivity improvement in the range of 0.6-0.9 dB. Another 0.9 dB is gained when increasing the FEC overhead from 7% to 34% corresponding to a bandwidth increase from 28 to 35 GHz.

4. Soft detection of LDPC-coded POL-QAM 6-4 modulation

An alternative way to transport the FEC overhead is to increase the number of bits per symbol and not only the symbol rate (bandwidth). Polarization QAM modulation [6] governs 9 constellation points rather than 8, as shown

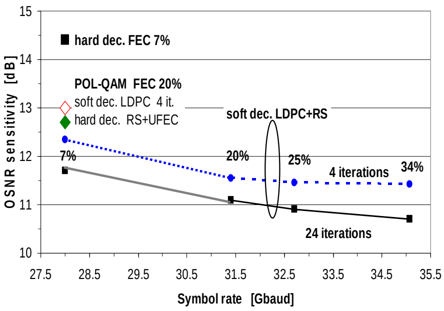


Fig. 3 *OSNR sensitivity (post FEC BER = 10^{-16}) vs. symbol rate for 100GbE PDM-QPSK signals with different LDPC codes of different rates. The FEC overhead including outer RS-code appears as percent value.*
Box: 7% hard dec. FEC reference
Solid line: 24 iterations, Dashed line: 4 iterations.

Diamonds : POL-QAM 6-4 modulation;
Hollow diamond: LDPC coded, soft-decision, 4 iter.
Filled diamond: RS(511,455) coded and hard-dec.

by Fig. 4. Hence 20% FEC overhead can be transported while keeping the symbol rate at 28 Gbaud. In Fig. 3 the OSNR sensitivity for the soft decision LDPC+RS with 20% overhead is indicated by a hollow diamond. For calculation of the LLR an extension of definitions for a single symbol [9] was used. For comparison purpose the box in Fig. 3 shows the sensitivity for an already discussed [6] hard decision scheme based on 7% outer FEC and a 13% inner RS(511,455) FEC. It is obvious that for POL-QAM 6-4 the soft-decision with a 20% LDPC (hollow diamond) does not lead to an improvement. We attribute this to error bursts due to the applied anti-Gray mapper.

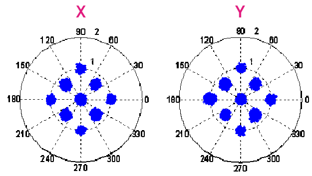


Fig. 4: *Constellation diagram (real/imaginary part) of X and Y polarization of the modulation format POL-QAM 6-4. The mapping of the bits to X and Y polarization is performed jointly and not independently as for PDM-QPSK [6].*

5. Summary

The sensitivity improvement which is achievable by increasing the FEC overhead while applying iterative soft-LDPC and hard RS decoding has numerically been assessed for a 100-Gbit/s PDM-QPSK transmission system. If the commonly assumed FEC code with 7% overhead is replaced by a soft-decided LDPC+RS code an sensitivity improvement beyond 2 dB can be expected (<12-dB OSNR). A bandwidth (symbol rate) increase from 28 to 35 GHz enables an increased FEC overhead of 34% which further improves the OSNR sensitivity to better than 10.7 dB. A potential realization with reduced complexity in the decoder was investigated by limiting the number of LDPC decoder iterations to only 4. The reduced processing degrades the sensitivity by approx. 0.7 dB. Since a concatenation of LDPC and RS decoder is applied, error free transmission can be guaranteed. Comparison with an alternative modulation scheme (polarization QAM, POL-QAM 6-4) with an extended constellation and hard-decision Reed-Solomon coding reveals no substantial improvement by soft-decision.

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