Multidimensional LDPC-Coded Modulation for Beyond 400 Gb/s per Wavelength Transmission

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***Abstract*—In this letter, we propose a multidimensional low-density parity-check-coded modulation scheme suitable for use in up to 400 Gb/s per wavelength transmission, using currently available commercial components operating at 40 gigasymbols/s. We show that we can achieve multiples of the current transmission speed with negligible penalty. At the same time, using this scheme, the transmission and signal processing are done at 40 gigasymbols/s, where dealing with all the nonlinear effects is more convenient and the polarization-mode dispersion is more manageable. In addition, we show that using the proposed technique, we can achieve an improvement ranging from 3 dB over 8-quadrature-amplitude modulation (QAM) to 14 dB over 256-QAM, and an improvement of up to 9.75 dB over the 256-3D-constellation at bit-error ratio (BER) of 10^{-9}. We also show that we can reach the 400-Gb/s aggregate rate with a coding gain of 10.75 dB at BER of 10^{-12}.**

***Index Terms*—High-speed optical transmission, low-density parity-check (LDPC) codes, multidimensional-coded modulation, optical communications, polarization-mode dispersion (PMD).**

I. Introduction

In RECENT years, optical communication systems have been evolving rapidly to adapt to the continuous increase in telecommunication needs. One major aspect that optical systems have to keep up with is the continuously increasing demand on transmission capacity. Such a demand stems mainly from the growing popularity of the Internet and multimedia in everyday life. According to some industry experts, 100-Gb/s transmission is needed by the end of 2009, while 1 Tb/s should be standardized by the year 2012–2013 [1]. Recent work by Ma *et al.* [2] provides an experimental demonstration of 1 Tb/s per wavelength transmission using 30-Gb/s coherent receiver. Unfortunately, adapting to higher transmission rates comes along with different obstacles such as degradation in the signal quality in addition to increased costs. Signal degradation is a result of different linear and nonlinear effects such as polarization-mode dispersion (PMD) and intrachannel nonlinearities. Consequently, the new optical communications solutions have to offer affordable upgrades of currently available optical communication systems operating at lower speeds to satisfy the required higher speeds. Utilizing currently available components avoids the added cost of producing faster, more complex components while avoiding the augmented degradation of performance that accompanies higher speed components.

In this letter, we propose the use of multidimensional low-density parity-check-coded modulation (N-D-LDPC-CM) to achieve beyond 400 Gb/s per wavelength transmission by employing currently available 40 Gb/s technology. This scheme enables even higher aggregate rates than the 3-D-LDPC-CM proposed by the authors in [3] due to the scalability of the implementation of the system, as will be shown in Section II. Using the currently available transmission equipment operating at 40 gigasymbols/s, this multidimensional scheme can achieve $N \times 40$ Gb/s aggregate rates, where $N = 1, 2, \ldots$ represents the total number of dimensions involved in the scheme.

By increasing the number of dimensions (i.e., the number of orthonormal basis functions), we can increase the aggregate rate of the system, while the use of LDPC coding grants reliable transmission at these higher speeds. The structured LDPC codes [4] used in this scheme improve performance by allowing easier iterative exchange of the *extrinsic* soft bit reliabilities between an *a posteriori probability* (APP) demapper and an LDPC decoder. Using this technique, we show that we can reach 400-Gb/s aggregate rate when keeping 10.75-dB coding gain at bit-error ratio (BER) of 10^{-12}. We also show an improvement that ranges from 6.25 dB over 8-3D-constellation to 16.25 dB over the 1024-3-D constellation proposed in [3] at BER of 10^{-9}.

II. Multidimensional LDPC-CM

The transmitter and receiver block diagrams are shown in Fig. 1. As shown in the setup, N different bit streams coming from different information sources are encoded using identical LDPC codes denoted by LDPC(n, k, r). These codes are of code rate $r = k/n$, where k is the number of information bits and n is the codeword length. The outputs of the encoders are interleaved by the $(N \times n)$ block interleaver. The block interleaver accepts data from the encoders row-wise, and outputs the data column-wise to the mapper that accepts N bits at time instance i. The mapper determines the corresponding M-ary $(M = 2^N)$ signal constellation point

$$s_i(t) = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} \phi_{i,j} \Phi_j(t) \quad (1)$$

as shown in Fig. 1(a). After this, the signals are modulated and sent over the fiber. In (1), which represents the general formula applicable to any multidimensional constellation, the set $\{\Phi_1(t), \Phi_2(t), \ldots, \Phi_N(t)\}$ represents a set of N orthonormal

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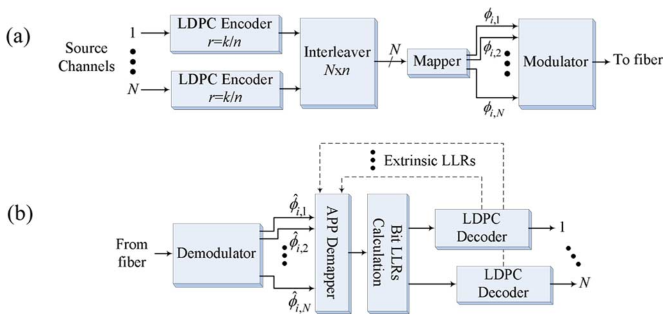

Fig. 1. Multidimensional bit-interleaved LDPC-coded modulation block diagrams: (a) transmitter and (b) receiver configurations.

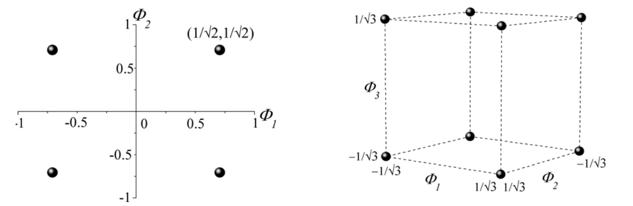

Fig. 2. N-D constellation diagrams for: (left) $N=2$ (QPSK) and (right) $N=3$ (eight-point 3-D constellation).

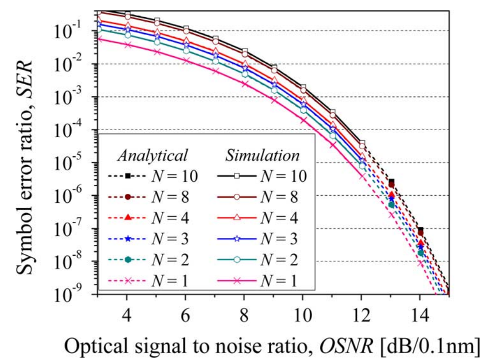

Fig. 3. SER performance of the uncoded modulation for different values of N. Solid lines: simulation results; dashed lines: analytical results.

basis functions and $\phi_{i,j} \in \{1,-1\}$. The M signals are at a distance of unity from the origin and form the vertices of an N-dimensional hypercube. The number N is determined by the desired final rate and the availability of orthogonal functions. If we take, for example, the desired aggregate rate to be 160 Gb/s, then we have to find four orthogonal functions to achieve 4 bits/symbol. For instance, phase provides the in-phase and the quadrature components; hence, the first two bits define the mapping of the signal on a conventional QPSK, while the third bit defines the polarization. The mapper will map 1 in the third bit to the x-polarization and -1 to the y-polarization. The fourth component can be frequency. The fourth bit is mapped to one of the two available orthogonal subcarriers depending on its value.

In the aforementioned example, $\phi_{i,j} \in \{1,-1\}$ means that each orthogonal function is modulated with binary phase-shift keying (BPSK) to reduce the complexity. The use of modulation formats of order higher than BPSK can further increase the throughput of the channel at the expense of increased complexity and performance degradation. By using BPSK in all dimensions, we keep the complexity low, while increasing the aggregate data rate with small degradation in BER performance, as long as the orthogonality among coordinates is preserved. In different scenarios, a compromise between bandwidth, power usage, and performance might be necessary. For instance, if we were to increase the total aggregate rate by adding another dimension using amplitude modulation or using pulse position modulation, we would be sacrificing power or bandwidth efficiency, respectively, even though we are increasing the channel throughput. In order to further improve the spectral efficiency, at the expense of performance degradation, the constellation coordinates can be changed to $\phi_{i,j} \in \{2m-M-1\}$, where $m=1,2,\ldots,M$, resulting in total number of constellation points $(N-1)M+2$ ($N-1$ basis function can have M points, except for the polarization for which $M=2$).

At the receiver side in Fig. 1(b), the outputs of the N branches of the demodulator are sampled at the symbol rate and the corresponding samples (at 40 gigasymbols/s) are forwarded to the APP demapper. The demapper provides the bit log-likelihood ratios (LLRs) required for iterative LDPC decoding. The bit LLRs required for LDPC decoding are calculated in bit LLRs calculation block. The LDPC decoder, in turn, forwards the extrinsic LLRs to the APP demapper, and the extrinsic information is iterated back and forth until convergence or until a predefined number of iterations is reached. These iterations between the LDPC decoder and the APP demapper are referred to as *outer iterations* in contrast to the *inner iterations*, which take place in the LDPC decoder. For detailed calculations of bit LLRs and the iterative operation, refer to [5]. The outer iterations help in improving the BER performance without compromising the complexity of the system. Extrinsic information transfer (EXIT) chart analysis [5], [6] has been used to select suitable LDPC codes for use in the proposed coded modulation scheme. In an N-D-LDPC-CM, the channels are decoded jointly, in a dependent manner, as to improve the system capability to compensate for any imbalance between orthogonal channels.

From the description of the transmitter and the receiver setup, it is clear that the system is scalable to any number of dimensions with negligible penalty, in terms of BER performance, as long as orthonormality is preserved. It is important to note that increasing the number of dimensions leads to an increased complexity, and so, a compromise between the desired aggregate rate and the complexity of the system is to be made in practice.

III. Simulation Results

Simulations were done over a linear channel model, with a symbol rate of 49.5 gigasymbols/s, for 20 iterations of sum–product algorithm for the LDPC decoder, and five or three outer iterations between the LDPC decoder and the natural demapper. We have observed different signal constellation formats, such as $N=1,2,3,4,8$, and 10, where N is the number of different basis functions. For $N=1$ and 2, the resulting constellations are the conventional BPSK and QPSK, respectively. The other constellations are referred to as N-D constellation. Fig. 2 shows different constellations for 2-D and 3-D.

Fig. 3 shows the uncoded symbol error probability as a function of the optical signal-to-noise ratio (OSNR) at a symbol rate of 40 gigasymbol/s. As shown in the figure, we present the analytical curves in addition to the simulation curves. We derived the analytical probability of symbol error as follows:

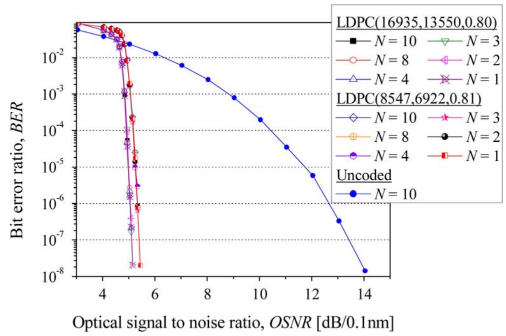

Fig. 4. BER performance of the N-D-LDPC-CM schemes for different LDPC codes in comparison with the uncoded case.

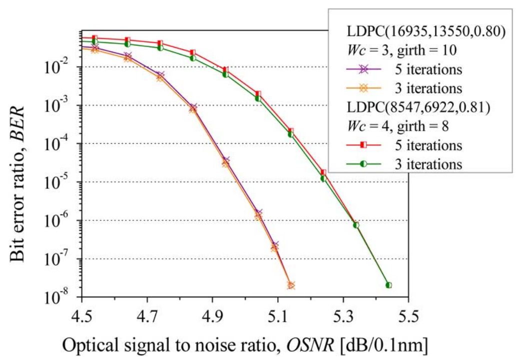

Fig. 5. BER performance of the N-D-LDPC-CM schemes for different LDPC codes after three and five outer iterations (W_c: column weight).

$$P_e = 1 - \left(1 - \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{\text{SNR}}{N}}\right)\right)^N \quad (2)$$

where $\operatorname{erfc}(x) = (2/\sqrt{\pi})\int_x^\infty \exp(-u^2)du$ is the complementary error function, SNR is the bit energy per bit to noise power spectral density ratio, and N is the total number of dimensions (equivalently, the number of bits per symbol).

It is important to note that the results achieved for the uncoded modulation for $N = 1$ and 2 are in accordance with the probability of symbol error figures [7, Figs. 5.2-12 and 5.5-16] for those of BPSK, QPSK, and 4-quadrature-amplitude modulation (QAM), taking into consideration the difference between the electrical SNR and the OSNR.

Fig. 4 shows the BER performance as a function of the OSNR at a symbol rate of 40 gigasymbol/s for the six N-D cases after five outer iterations in comparison with the uncoded case. As shown in the figure, LDPC (8547, 6922, 0.81) code achieves 8.5-dB gain over the uncoded case at BER of 10^{-8}, while the LDPC (16935, 13550, 0.80) code achieves a gain of 9 dB at the same BER level.

As noted from Fig. 3, increasing the number of dimensions and also increasing the aggregate rate does not introduce a high penalty. Since increasing N from 1 to 10 and getting ten times higher speed hardly results in 0.7-dB penalty at a symbol-error ratio (SER) of 10^{-7}, and even less at lower SER as the curves start to converge. This result is obvious in terms of BER as well, since in Fig. 4 the curves for all different N are almost overlapping.

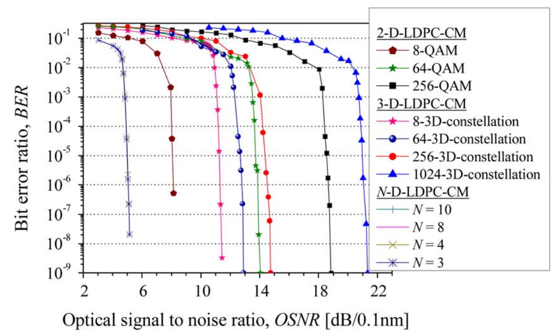

Fig. 6. BER performance of the 2-D, 3-D, and N-D-LDPC-CM schemes for different constellations.

Fig. 5 shows the BER performance as a function of the OSNR at a symbol rate of 40 gigasymbol/s, both LDPC codes after five and three outer iterations for $N = 3$. As noted from the figure, the results for each code are quite similar for all the dimensions and different numbers of outer iterations. The major improvement factor of the BER performance is the LDPC code used. Different factors affect the performance of LDPC codes such as codeword length, column weight (W_c), and girth, but these effects are outside the scope of this letter.

Fig. 6 shows a comparison of the BER performance among the conventional QAM, 3-D-LPDC-CM, and the proposed scheme. The improvement of the proposed scheme, while insuring orthogonality, is reported at BER of 10^{-9} to be: 3 dB over 8-QAM, 6.25 dB over 8-3D-constellation, 9.75 dB over 256-3D-constellation, 14 dB over 256-QAM, and 16.25 dB over 1024-3D-constellation.

IV. Conclusion

The novel multidimensional LDPC-coded modulation scheme proposed in this letter enables optical transmission beyond 400 Gb/s in aggregate rate using currently available commercial components operating at 40 gigasymbols/s while keeping coding gains as high as 10.75 dB. The proposed scheme introduces higher transmission speeds in addition to significant performance improvements that range from 3 dB over 8-QAM to 14 dB over 256-QAM. The scheme is based on a multidimensional signal constellation, and the receiver is based on the APP demapper, and LDPC decoder.

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