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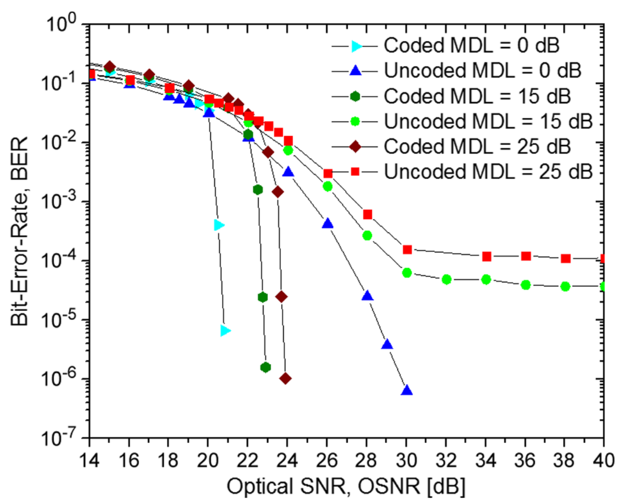

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Nonbinary LDPC-Coded Mode-Multiplexed Coherent Optical OFDM 1.28-Tbit/s 16-QAM Signal Transmission Over 2000 km of Few-Mode Fibers With Mode-Dependent Loss

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Abstract: We demonstrate the possibility of nonbinary LDPC-coded mode-multiplexed coherent optical OFDM 1.28-Tbit/s 16-QAM signal transmission over 2000 km of few-mode fiber (FMF) with mode-dependent loss (MDL) by using an advanced mode-coupling compensation scheme. The performance of proposed coded-modulation scheme is evaluated for different number of spatial modes. The simulation results indicate that the MDL is the predominant effect in the long-haul optical transmission based on FMFs. Different pilot-aided OFDM based compensation methods are studied, and it has been found that minimum mean-square estimation with linear interpolation method is the most robust against mode coupling and MDL. We also show that the nonbinary LDPC-coded modulation provides about 1 dB improvement over binary LDPC-coded modulation (16 QAM OFDM and MDL of 25 dB). Finally, we study the degradation of increasing the number of modes and investigate the proposed scheme for different MDL values in both four- and eight-mode fibers.

Index Terms: Microwave photonics signal processing, nonbinary LDPC-coded modulation, orthogonal frequency-division multiplexing (OFDM), few-mode fiber (FMF) communications, multi-Tb/s optical transport.

1. Introduction

The Internet has fundamentally changed the way of modern communication. Current trends indicate that high-capacity demands are not going to be saturated anytime soon. From Shannon's theory, we know that information capacity is a logarithmic function of signal-to-noise ratio (SNR) but a linear function of the number of dimensions [1]. In order to satisfy never-ending capacity demands, there are several attempts to employ additional degrees of freedom in transmission system, which can dramatically improve the spectral efficiency [2].

Development of few-mode fiber (FMF)-based optical transport systems is an attractive pathway to satisfy high capacity demands [3]. FMFs have a core diameter larger than SMF, which allows the propagation of several modes while not overwhelming the computation capacity of silicon chips to compensate for mode coupling. Unfortunately, FMFs exhibit differential mode delay (DMD),

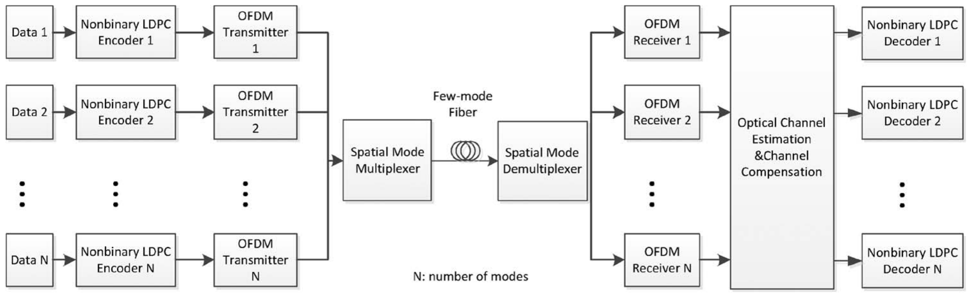

Fig. 1. Block diagram of the proposed nonbinary LDPC OFDM system over FMFs.

mode-dependent loss (MDL), and random coupling between the supported modes, which will dramatically reduce the system reach without employing advanced channel estimation and distortion compensation schemes.

To overcome the disadvantages of using FMF, the orthogonal frequency-division multiplexing (OFDM) is an excellent candidate [4]. Combined with advanced compensation methods and nonbinary LDPC coding, OFDM system over FMFs can enable ultrahigh capacity optical transport.

In this paper, we propose the nonbinary LDPC-coded mode-multiplexed coherent optical OFDM scheme suitable for optical transmission over more than 2000 km by employing FMFs. We evaluate the performance of the proposed mode-multiplexed OFDM system equipped with powerful channel estimation and compensation techniques [5]. The numerical results indicate that the proposed nonbinary LDPC-coded OFDM system with least minimum mean-square error (LMMSE) estimation with linear interpolation is the best compromise among performance and complexity. The coding gain of nonbinary LDPC increases as either number of modes or constellation size increases. We also provide the BER performance evaluation under different gain and loss profiles. In addition, we demonstrate possibility of 50G symbol/s serial optical transmission over 2000 km of FMF when nonbinary LDPC-coded 16 QAM and eight modes are used with aggregate data rate of 1.28 Tb/s.

The remainder of the paper is organized as follows: Section 2 provides the details of proposed nonbinary quasi-cyclic (QC) LDPC-coded mode-multiplexed OFDM system. Section 3 describes the channel model that takes into account the group delays and different gain and loss profiles. In Section 4, the simulation setup is described, and result results of simulations are provided. Finally, the conclusion is made in Section 5.

2. Proposed Nonbinary LDPC-Coded Mode-Multiplexed Coherent Optical OFDM System

2.1. Description of Proposed Mode-Multiplexed Coherent Optical OFDM Scheme

The proposed nonbinary LDPC-coded mode-multiplexed coherent optical OFDM scheme is shown in Fig. 1. The *N*-independent data streams from different information source are encoded by nonbinary QC LDPC codes. After the encoder, the OFDM transmitter processes the data streams in a conventional way [5]. The mapper accepts the nonbinary symbols from nonbinary LDPC encoder and maps them to the corresponding M-ary constellation points. The OFDM transmitter then inserts the training frames and pilot symbols into the OFDM frames for adequate channel estimation, followed by the inverse fast Fourier transform (IFFT) calculation, cyclic extension, and digital-to-analog (D/A) conversion. In Fig. 2(a), the OFDM transmitter configuration is provided. The OFDM transmitter performs several main steps. Initially, it inserts pilots in specific positions, before the information frames, or inside the information frames. Second, the M-ary symbols are zero padded in the middle and used as the input samples of IFFT block. Third, it performs cyclic extension. The length of the guard interval is properly chosen to be longer than the total spread due to mode dispersion. Finally, the D/A conversion is performed followed by I/Q modulator. After D/A conversion, the real and imaginary parts of such obtained OFDM stream are used as I and Q inputs

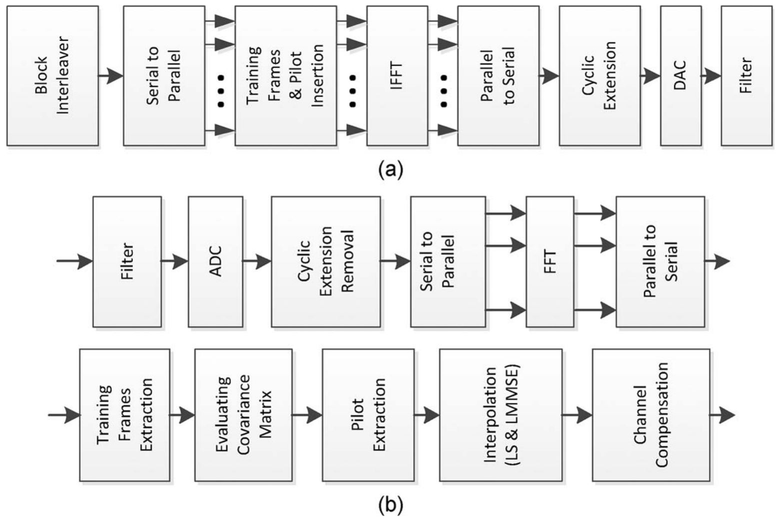

Fig. 2. Block diagram of the transmitter and receiver architectures for the proposed scheme: (a) OFDM transmitter module configuration and (b) OFDM receiver module architecture and channel estimation and compensation steps.

of I/Q modulator. The N-independent OFDM streams are mode multiplexed and simultaneously transmitted over FMF transmission line. On receiver side, after mode demultiplexing, we perform conventional coherent detection, followed by analog-to-digital conversion, cyclic extension removal, and FFT calculation. The coherent detection is used to detect the OFDM signals after 2000 km of FMF transmission. In OFDM receiver, we perform the channel estimation based on pilot tones, followed by mode coupling compensation, with different steps shown in Fig. 2(b).

Two different criteria for OFDM channel estimation, namely, the least square (LS) and LMMSE schemes are used in combination with channel interpolation based on either piecewise linear interpolation or piecewise second-order interpolation [5]. Therefore, four different ways of compensation of mode coupling have been evaluated. The complexity of LMMSE algorithm is higher than that of LS. It requires the use of training sequences to estimate correlation matrices and OSNR. In addition, the matrix inversion is needed. On the other hand, it provides significant improvement in BER performance when compared with LS estimation, as shown in Section 4. This is the reason why we use the reduced-complexity LMMSE algorithm, described in [5] (see also [11]). Other methods that can be used, in addition to LS and LMMSE methods, include various forms of equalizers and maximum-likelihood sequence estimation (MLSE). However, the use of finite impulse response (FIR) filters requires too many taps to compensate for various linear impairments in FMFs for distances of several thousand kilometers. This method also suffers from noise enhancement phenomenon. On the other hand, the complexity of MLSE grows exponentially with signal constellation size and channel memory. Therefore, it appears that MMSE is a good compromise among complexity and performance, in particular when used in combination with OFDM.

2.2. Description of Nonbinary QC-LDPC Codes

Nonbinary LDPC codes were first investigated by Davey and Mackay in 1998 [6]. We know that nonbinary LDPC codes constructed over higher order Galois fields exhibit superior performance than the binary codes. They also gave an efficient method of decoding using the FFT. In this paper, we use the high-rate nonbinary regular QC-LDPC codes [7], [9], [10] due to highly regular structure of their parity-check matrices, which will facilitate hardware decoder implementations, in combination with mode-multiplexed OFDM.

The most important characteristic of LDPC codes is the sparseness of ones in their parity-check matrices. In addition to this property, the parity-check matrices of QC-LDPC codes can be generated as an array of many submatrices, which have the same size. The parity check matrix can be organized as:

$$\mathbf{H} = \begin{bmatrix} H_{0,0} & H_{0,1} & \cdots & H_{0,\rho-1} \\ H_{1,0} & H_{1,1} & & H_{0,\rho-1} \\ \vdots & & \ddots & \vdots \\ H_{\gamma-1,0} & H_{\gamma-1,0} & \cdots & H_{\gamma-1,\rho-1} \end{bmatrix}$$

where $H_{i,j}$, $0 \le i \le \gamma - 1$, $0 \le j \le \rho - 1$ is a B $\times$ B submatrix in which each row is a cyclic shift matrix. The QC-LDPC codes can greatly reduce the complexity of the implementation. Instead of zeros and ones, used in binary LDPC code, we use the Galois field of q elements, such as GF(q), in the code design, to obtain a q-ary LDPC codes. Nonbinary QC-LDPC codes can be constructed by randomly replacing the ones in parity check matrix of binary QC-LDPC code [7].

In summary, nonbinary QC LDPC codes are designed as follows: 1) The starting point is the binary parity-check matrix, designed as an array of many small binary LDPC submatrices that have the same size, but each row is a cyclic shifted of previous row. 2) Ones in binary parity-check matrix are replaced by randomly selected nonzero elements from GF(2^2). 3) The Gaussian elimination is used to obtain the nonbinary QC-LDPC generator matrix.

3. Modeling of FMFs With MDL

The main characteristics of the FMFs are DMD and mode-dependent gain and loss, which can be referred to as MDL. When it comes to long-haul transmission system, which contains many inline optical amplifiers and switches, the MDL will be introduced. Unlike the modal delays, which can be compensated nicely as we showed in [5], the MDL can be a fundamental limitation of the performance.

Both DMD and MDL have specific probability distributions. It has been shown in [8] that the distribution of MDL can be completely specified by the number of modes N, the number of FMF sections K, and MDL standard deviation of each section σ_g. The standard deviation of accumulated MDL after K FMF sections can be related to σ_g as $\xi = \sqrt{K}\sigma_g$. Modal group delays in FMFs in the strong-coupling regime can be obtained by calculating the zero-trace random Gaussian Hermitian matrix with eigenvalues corresponding to the DMD. We model the FMFs as a concatenation of numerous sections with independent characteristics, with each section being shorter than the correlation length.

The relation between overall MDL standard deviation σ_{mdl} and accumulated MDL standard deviation ξ can be written as [8],

$$\sigma_{mdl} = \xi\sqrt{1 + \frac{1}{12}\xi^2}.$$

The accumulated MDL variance ξ can be obtained by $\xi = \sqrt{K}\sigma_g$, where σ_g is the MDL standard deviation of each section. The response of each section in frequency domain can be determined as,

$$M_k(\omega) = V_k\Lambda_k(\omega)U_k^{\dagger}, \quad k = 1, 2, \ldots, K$$

where V_k and U_k are frequency-independent complex random unitary matrices, while $\dagger$ denotes Hermitian transpose. In equation above, $\Lambda_k(\omega)$ denotes a diagonal matrix representing both MDL and modal dispersion in the Kth section. $\Lambda_k(\omega)$ can be expressed as [8]

$$\Lambda_k(\omega) = \mathrm{diag}\left[e^{\frac{1}{2}g_1^{(k)} - j\omega\tau_1^{(k)}}, e^{\frac{1}{2}g_2^{(k)} - j\omega\tau_2^{(k)}}, \ldots, e^{\frac{1}{2}g_D^{(k)} - j\omega\tau_D^{(k)}}\right].$$

The vectors $\vec{g}^{(k)} = (g_1^{(k)}, g_2^{(k)}, \ldots, g_D^{(k)})$ and $\vec{\tau}^{(k)} = (\tau_1^{(k)}, \tau_2^{(k)}, \ldots, \tau_D^{(k)})$ describe the uncoupled modal groups delays and MDL, respectively. Each FMF section has a modal gain profile $g_i^{(k)} = \pm\alpha$, where $\alpha = \sigma_g$. In the simulation, we set the first half of the modes to have gain of $+\alpha$, and the last half of the modes to have loss of $-\alpha$, such that the overall gain sum is zero.

TABLE 1

OFDM system parameters

FFT/IFFFT length	Data subcarrier size	Pilot subcarrier size	Symbol size	Cyclic extension length
4096	1920	128	2048	128
Number of modes	Modulation format	Number of training frames	Sampling rate	Oversampling factor
4/8	16QAM	80	50GS/s	8

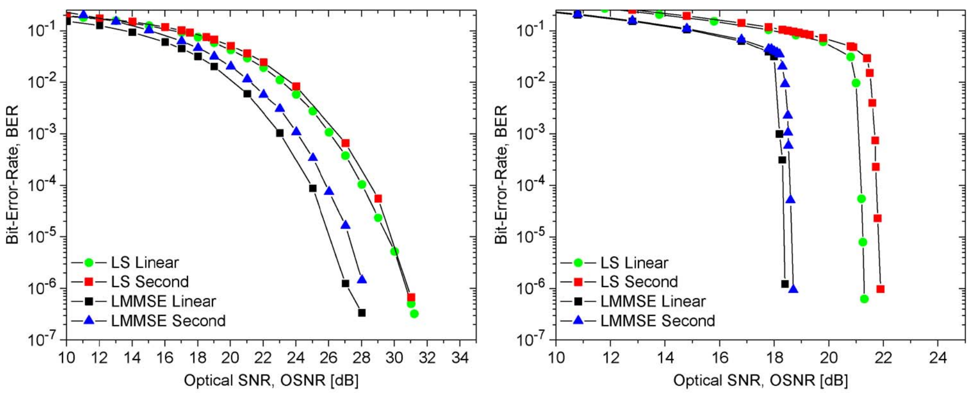

Fig. 3. Bit-error-rate analysis at baseband information rate per mode of 160 Gb/s for 16 QAM in four-mode fiber after 2000 km of FMF for different channel estimation techniques when MDL is set to zero: (a) uncoded case and (b) nonbinary LDPC-coded case.

The overall transfer matrix of FMF having K sections can be found as a product of transfer matrices of individual sections:

$$\mathrm{M_{tot}}(\omega) = \mathrm{M_k}(\omega)\ldots\mathrm{M_2}(\omega)\mathrm{M_1}(\omega).$$

4. Simulation Setup and Results

To demonstrate high potential of proposed system, we perform the Monte Carlo simulation and study BER performance of the system for different OFDM-based compensation methods. The numerical results represent the BER results averaged over all modes. We employ in simulations regular nonbinary QC-LDPC (16 935, 13 550) code of column weight three and girth ten [9]. The improvement of using the nonbinary codes in OFDM system is also studied. The OFDM system parameters are summarized in Table 1.

Fig. 3 shows both uncoded BER and nonbinary LDPC-coded coded BER for different channel estimation methods for 16 QAM when using nonbinary LDPC codes. It is easy to see that the LMMSE with linear interpolation compensation performs the best. However, LMMSE requires more training symbols in front of the data and takes more time for correlation matrices estimation.

Fig. 4(a) shows the different between binary LDPC and nonbinary LDPC code in OFDM system. Notice that the nonbinary LDPC performs better than binary when increasing the constellation sizes or MDL. For MDL of 25 dB, the nonbinary LDPC-coded scheme outperforms by 0.7 dB (at BER of 10^{-5}) corresponding nonbinary LDPC-coded QPSK, and there is about 1 dB (at BER of 10^{-5}) gap when using the 16 QAM. We also notice that the gaps between nonbinary and binary are 0.6 dB and 1 dB when increasing the MDL from 0 dB to 25 dB. Notice that, for MDL of 25 dB, both uncoded QPSK and uncoded 16-QAM exhibit error floor phenomenon.

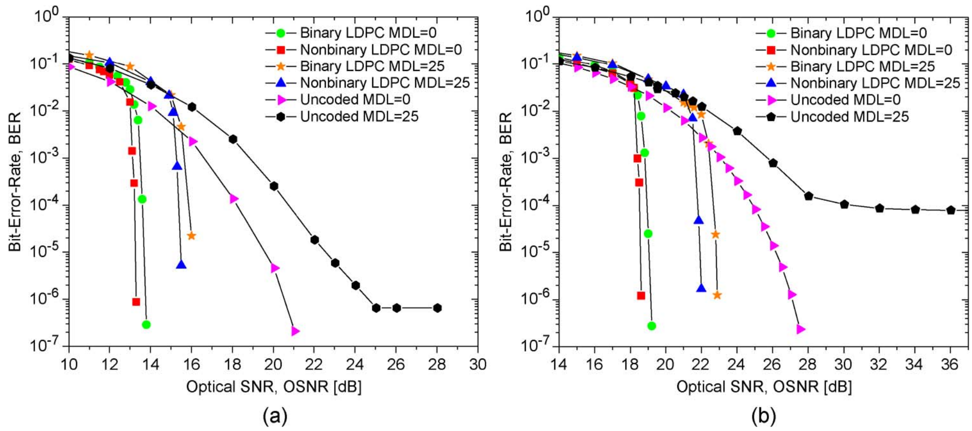

Fig. 4. Bit-error-rate performance of LDPC-coded QPSK/16 QAM over 2000 km of FMF by using LMMSE with linear interpolation when MDL = 0: (a) QPSK and (b) 16 QAM.

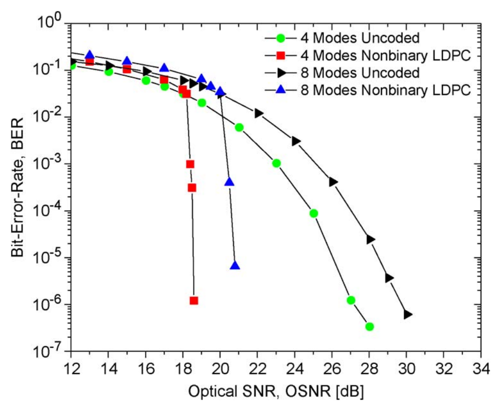

Fig. 5. Degradation of bit-error-rate performance when the number of modes is increased from four to eight in 16-QAM OFDM system, after 2000 km FMF by using LMMSE with linear interpolation, for MDL = 0 dB.

In Fig. 5, we evaluate the BER performance degradation when the number of modes is increased from four to eight. At BER of 10^{-6}, we have found that the increase of number of modes from four to eight leads to 3.5-dB degradation.

In Fig. 6(a), we study the performance of proposed scheme for different MDL values. There is about 2.5-dB degradation in OSNR (at BER of 10^{-6}) when the MDL is increased from 0 dB to 15 dB in coded case. On the other hand, when MDL is increased by additional 10 dB, we are facing additional 1-dB degradation in OSNR. The OFDM system can compensate for various channel distortions for MDL ranging from 0 dB to 25 dB, for OSNR values below 25 dB. When increasing the number of modes from four to eight, as it can be seen in Fig. 6(b), the similar performance trend has been found, except that all BER plots have been shifted to higher OSNR values. It is interesting to notice that the uncoded OFDM error floor phenomenon is more pronounced as either the MDL increases or number of modes increases. The aggregate data rate of system based on four fiber modes, with two polarizations each, and 16-QAM is 50 GS/s $\times 4 \times 4 \times 2 \times 0.8 = 1.28$ Tb/s, where the first factor 4 comes from the fact that, in 16 QAM, 4 bits/symbol are transmitted, the second factor 4 comes from 4 modes being employed, factor 2 for two polarizations, and factor 0.8 is the code rate of LDPC code.

As an illustration of efficiency of LMMSE estimation with linear interpolation in dealing with mode coupling, DMD, and MDL, in Fig. 7, we show constellation maps before and after compensation for

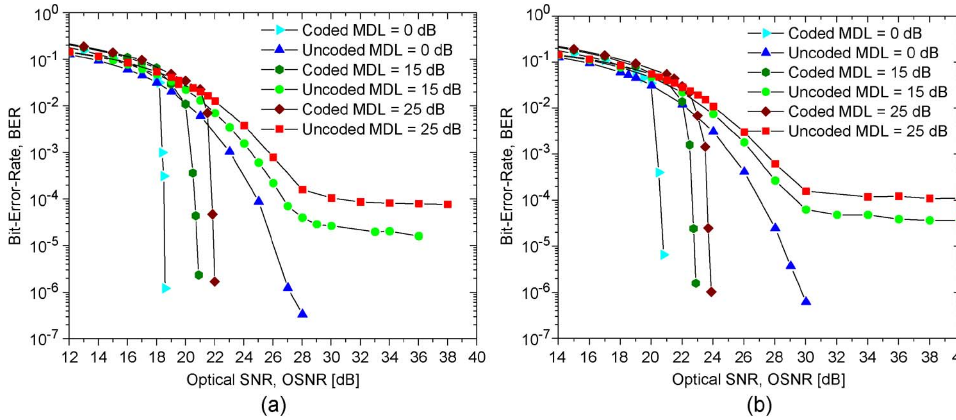

Fig. 6. Bit-error-rate performance for different MDL values at baseband information rate per mode of 160 Gb/s for 16 QAM in four-mode fiber after 2000 km based on nonbinary LDPC coding and LMMSE estimation with linear interpolation: (a) the number of modes is four and (b) the number of modes is eight.

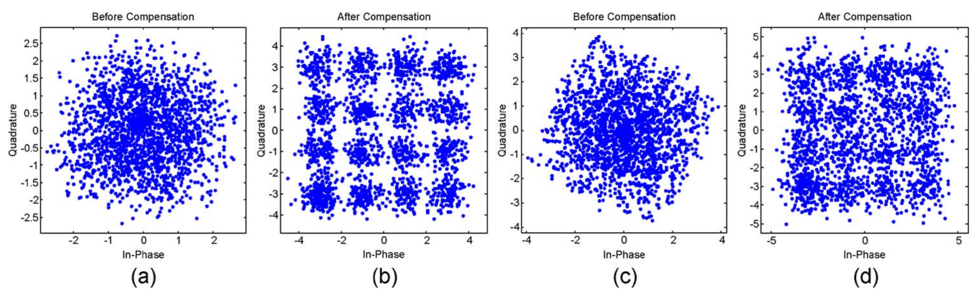

Fig. 7. Constellation maps of a 16-QAM signal before and after LMMSE estimation with linear interpolation for different MDL values, when OSNR = 22 dB: (a) before the compensation when MDL = 0, (b) after the compensation when MDL = 0, (c) before the compensation when MDL = 25 dB, and (d) after the compensation when MDL = 25 dB.

two different MDL values (0 and 25 dB). Regarding the influence of DMD, it is comparable with that of DGD in SMF systems, as described in [12]. However, this study is out of scope of this paper.

5. Conclusion

Development of FMFs and corresponding coded mode-multiplexed technologies represents a promising pathway to satisfy never-ending capacity demands. To evaluate the proposed nonbinary LDPC-coded mode-multiplexed scheme, we performed the Monte Carlo simulations for different scenarios. We initially evaluated the performance of nonbinary LDPC OFDM system over a 2000-km FMFs with different compensation methods. The LMMSE with linear interpolation has been shown to be more robust compared to LS estimation, but it also requires a more complicated algorithm for compensation. Second, we compared the binary and nonbinary LDPC code, which shows that nonbinary LDPC is about 1 dB better than binary LDPC in 16-QAM case (at BER of 10^{-6}) with MDL = 25 dB, and it is expected that the gap will be larger if larger constellation size is used. Next, we studied the degradation when the number of modes get increased from four to eight. This increase in number of modes has resulted in about 3.5-dB degradation for nonbinary LDPC-coded mode-multiplexed 16-QAM OFDM (at BER of 10^{-6}). We have also found that the error floor of uncoded OFDM gets more pronounced as either the number of modes or MDL get increased. Although the FMFs with group delay and MDL degrades the BER performance, the use of strong FEC and powerful compensation method has enabled beyond 1-Tb/s optical transport over 2000 km of eight-mode fiber. Equipped with powerful channel estimation and compensation techniques, the proposed nonbinary LDPC-coded mode-multiplexed scheme represent a promising candidate for future multi-Tb/s optical transport systems over distances exceeding several thousands of kilometers.

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