electronics

Article

Investigation of IEEE 802.16e LDPC Code Application in PM-DQPSK System

Jiaxin Xue [1,2], Yupeng Li [1,2,*], Yichao Zhang [1,2], Xiao Wu [1,2] and Yanyue Zhang [1,2]

1 College of Electronic and Communication Engineering, Tianjin Normal University, Tianjin 300387, China;
2 Tianjin Key Laboratory of Wireless Mobile Communication and Power Transmission, Tianjin Normal University, Tianjin 300387, China
* Correspondence: fx_lyp@163.com

Abstract: With the development of the Internet and information technology, optical fiber communication systems need to meet people's information demand for large capacity and high speed. High-order phase modulation and channel multiplexing can improve the capacity and data rate of optical fiber communication systems, but they also bring the problem of bit error. To improve the transmission quality and reliability of optical fiber communication systems, forward error correction (FEC) coding techniques are commonly used, which serve as the fundamental approach to enhance the quality and reliability of fiber optic communication systems, ensuring that the received data remain accurate and reliable. The FEC in optical fiber communication systems is divided into three generations. The first generation FEC is mainly hard decision codewords, represented as RS code. The second generation FEC is mainly cascaded code, which stands for interleaved cascaded code. The third generation of FEC mainly refers to soft decision codes, which are represented as low-density parity-check (LDPC) codes. As a kind of FEC, LDPC codes stand out as pivotal contributors in the field of optical communication and have gained remarkable attention due to exceptional error correction performance and low decoding complexity. Based on IEEE802.16e standard, LDPC code with specific code length and rate is compiled and simulated in MATLAB and VPItransmissionMaker 10.1 and successfully incorporated into polarization multiplexed differential quadrature phase shift keying (PM-DQPSK) coherent optical transmission system. The simulation results indicate that the bit error rate (BER) can be reduced to 10^{-3} when the optical signal-to-noise ratio (OSNR) reaches 14.2 dB, and the BER experiences a reduction by nearly three orders of magnitude when the OSNR is 17.2 dB. These findings underscore the efficacy of LDPC codes in significantly improving the performance of optical communication systems, particularly in scenarios demanding robust error correction capabilities. This study provides valuable, significant results regarding the potential of LDPC codes for enhancing the reliability of optical transmission in real-world applications.

Keywords: optical fiber communication; FEC; IEEE802.16eLDPC; PM-DQPSK; OSNR

Citation: Xue, J.; Li, Y.; Zhang, Y.; Wu, X.; Zhang, Y. Investigation of IEEE 802.16e LDPC Code Application in PM-DQPSK System. *Electronics* **2024**, *13*, 1887. https://doi.org/10.3390/electronics13101887

Academic Editor: Nakkeeran Kaliyaperumal

Received: 11 April 2024
Revised: 9 May 2024
Accepted: 10 May 2024
Published: 11 May 2024

1. Introduction

Since the inception of the first optical fiber, optical fiber communication has been dominating the communication market due to its numerous advantages. In recent years, with the rapid development of communication and information technology, optical fiber communication has emerged as the primary mode of data transmission. Optical fiber communication boasts not only large transmission capacity, high transmission speed, and extensive relay distance but also excellent security and immunity to external electromagnetic interference. Its lightweight and cost-effectiveness have cemented its status as a hallmark of the information age, playing an indispensable role in facilitating social information exchange [1].

In the current stage of rapid development, optical fiber communication has the advantages of long-distance transmission, dense wavelength division multiplexing, fiber to the home, etc., and has become the key foundation to meet the needs of the Internet, 5G, Internet of things, and other applications for stable and efficient data transmission. In the future, with the continuous development of quantum communication technology, it will continue to play an important role in providing reliable support for the progress of digital society. However, with the development of optical fiber communication, the demand for transmission capacity and transmission distance is increasing due to the influence of noise, nonlinear effects of fiber, chromaticity dispersion, and polarization mode dispersion; the development and application of high-rate long-distance optical communication are limited [2,3]. The high rate and large capacity optical fiber transmission system is mainly realized by high order modulation code pattern and intensive multiplexing technology. They have high requirements on optical signal-to-noise ratio (OSNR), especially high-order modulation techniques, which increase spectrum utilization while reducing the Euclidean distance between symbols, making phase states difficult to distinguish [4]. As a result, OSNR is the main factor limiting the transmission rate of the system. In recent years, the rapid growth of the optical fiber communication rate has been attributed to the strong support of advanced optical technology and forward error correction technology. Forward error correction (FEC) technology has long been used in electrical communication systems. It is the main technology to improve the reliability of digital communication systems and reduce the bit error rate. It has been widely used in deep-space communication, satellite communication, mobile communication, and computer networks. The FEC can greatly reduce the OSNR requirements of the system and reduce the bit error rate, so FEC is an indispensable part of the optical fiber communication system. The primary purpose of channel coding is to enhance the reliability of information transmission and fortify resistance against interference. Following source coding, a sequence composed of '0' and '1' undergoes encoding based on specific coding rules. By adding redundant code elements, the original random distributed code word sequence has a certain regularity. At the receiving end, the code is decoded based on the encoding correlation, errors are checked, and the original, error-free code word sequence is restored.

In an optical transmission system, the forward error correction technique can eliminate the bit error rate (BER) plateau phenomenon in the system performance curve, and its coding gain also provides a certain amount of system prosperity so as to reduce the impact of linear and nonlinear factors in optical links on the system performance. Especially for the optical amplification system, the optical amplifier interval can be increased, the transmission distance can be extended, the channel rate can be increased, and the channel optical power can be reduced.

There are many kinds of forward error correction codes. At present, Low-density parity-check (LDPC) stands out for its ability to complete correct decoding in optical fiber communication systems with extremely low OSNR. LDPC was proposed by Gallager in the 1960s, which is a linear block code characterized by a sparse parity check matrix, and it has fewer non-zero elements and more zeros, hence the name. Although it has excellent error correction performance, the advantages of LDPC remained overlooked for decades due to the lack of effective computational methods in the 1960s, and encoders at that time believed that serial codes performed better [5]. Tanner studied the LDPC code from a graphical point of view in 1981, and the Tanner diagram shows the decoding process of the LDPC code directly. From Tanner's diagram, the decoding process of LDPC code became visually comprehensible [6]. Until the mid to late 1990s, MacKay rediscovered that LDPC code was also a good code with performance close to Shannon limit under AWGN channel, coupled with low realization complexity [7], and popularized Gallager's probabilistic iterative decoding algorithm, which greatly promoted the development of LDPC code [8].

Recent research on LDPC highlights its remarkable performance, nearing the theoretical Shannon limit, which underscores its efficacy in achieving optimal communication reliability. LDPC codes offer advantages over traditional Reed–Solomon (RS) codes and convolutional codes due to their simpler coding structure and lower decoding complexity [9]. Compared with Turbo code, LDPC code is proven to have stronger error correction capability and lower error rate in long coding, and the iterative decoding algorithm of LDPC is a parallel algorithm with low decoding delay [10,11]. Moreover, LDPC codes have shown better performance relative to polar codes in optical communication systems, especially under high SNR conditions, where LDPC codes generally have lower bit error rates and higher reliability [12]. Additionally, LDPC codes excel in large-scale data transmission and high-rate communication, such as long-distance and high-rate optical communication, owing to their comparatively low decoding complexity. As a result, LDPC codes have been widely recognized as a superior performance and efficient forward error correction coding technique in optical communication systems.

The paper discusses the application of IEEE80.216e LDPC codes in optical fiber communication systems to improve system performance. The contents of this paper are as follows: Section 1 introduces the research background and significance; Section 2 discusses the construction of IEEE 802.16e standard LDPC code, where Section 2.1 discusses the construction of IEEE 802.16e Standard H-matrix, and Sections 2.2 and 2.3 discuss the fast iterative coding algorithm and belief propagation (BP) decoding algorithm; Section 3 discusses the PM-DQPSK system and simulation results, where Sections 3.1 and 3.2 discuss the PM-DQPSK coherent optical transmission system setup and the digital signal processing (DSP) algorithm, and the simulation results are discussed in Section 3.3. Finally, the conclusion is given in Section 4.

2. IEEE 802.16e Standard LDPC Code Construction

2.1. Construction of IEEE 802.16e Standard H-Matrix

With the continuous development of coherent optical communication technology, LDPC codes have been widely adopted in optical fiber communication systems, especially the PM-DQPSK system, which heavily depends on error control coding techniques to improve the quality and reliability of data transmission. LDPC codes stand out for their excellent performance close to the Shannon limit, which has the remarkable advantage of consistently low BER. This characteristic makes LDPC codes an indispensable part of optical fiber communications, and they play an important role in advancing the quality and efficiency of communication [13]. LDPC codes have also emerged as a crucial tool in ensuring reliable and high-performance data transmission over long distances in optical fiber communication systems.

The defined LDPC code in IEEE802.16e standard is a quasi-circular irregular LDPC code, in which different code rates have different check matrices H. H_b is the base checksum matrix of H, and H is obtained by extending its base checksum matrix H_b, where H_b is a matrix with m_b rows and n_b columns.

$$H_b = \left[(H_{b1})_{m_b \times (n_b - m_b)} | (H_{b2})_{m_b \times m_b} \right] \tag{1}$$

According to the IEEE802.16e standard, the length of n_b is fixed to 24, while the length of m_b varies with the code rate. H_{b1} in Equation (1) corresponds to the information bits, which is a matrix of size $m_b \times (n_b - m_b)$, and H_{b2} is a matrix with both rows and columns being m_b. Among them, the first column of H_{b2} has $h(1)$, $h(r)$, and $h(m_b)$ as non-negative integers with $h(1) = h(m_b)$. r ranges from $2 \leq r \leq m_b - 1$; the exact value is specified by the IEEE802.16e standard. The matrix H_{b2} can be formed into a quasi-bi-diagonal structure in all rows except the first column, and the values on both quasi-diagonals are 0, and all other positions are -1. The elemental composition of H_{b2} is shown in Equation (2).

$$H_{b2} = \begin{bmatrix} h(1) & 0 & & & & & & & \\ -1 & 0 & 0 & & & & & & \\ \vdots & & 0 & & 0 & & -1 & & \\ -1 & & & 0 & \ddots & & & & \\ h(r) & & & & \ddots & \ddots & & & \\ -1 & & & & & & 0 & & \\ & & & & & \ddots & & & \\ \vdots & & -1 & & & & 0 & 0 & \\ -1 & & & & & & & 0 & 0 \\ h(m_b) & & & & & & & & 0 \end{bmatrix} \tag{2}$$

H_b can be extended by the operation of $m_b q \times n_b q$ to obtain the check matrix H, where q is called the expansion factor [14]. There are 19 values of q, corresponding to 19 code lengths; the minimum is 24, the maximum is 96, and H_b is extended according to the rules [15]. The element of H_b in position (i, j) is $q(i, j)$,

$$q(i,j) = \begin{cases} q(i.j), & q(i,j) \leq 0, \\ \left\lceil \frac{q(i,j) \times z}{96} \right\rceil, & q(i,j) > 0. \end{cases} \tag{3}$$

After updating, if $q(i, j)$ is -1, the replacement is to be performed with the zero matrix of row z and column z, while if $q(i, j)$ is a non-negative integer, the replacement is to be performed with the matrix of z rows and z columns, and this matrix of z rows and z columns is obtained by cycling right from $q(i, j)$. After replacing all the values inside the base-check matrix H_b with the matrix of z rows and z columns, the corresponding check matrix H of the LDPC codes at various code lengths and code rates can be obtained.

2.2. LDPC Encoding Algorithm

Leveraging the sparsity of the check matrix H for LDPC coding is an effective approach. This approach capitalizes on the fact that the majority of elements in the check matrix H are zero, leading to efficient encoding and decoding processes. By exploiting this sparsity, LDPC codes can achieve high performance with relatively low computational complexity. Furthermore, this characteristic enables the development of fast iterative coding algorithms that efficiently operate on the sparse structure of the matrix, facilitating rapid encoding and decoding of data. A fast iterative coding algorithm that takes advantage of this sparsity is described below [16].

Encoding is the process of obtaining a check digit v from a given set of information code elements u. According to the conventions of the LDPC code of the IEEE 802.16e standard, the information code element can be regarded as consisting of $k_b(k_b = n_b - m_b)$ vectors of $z \times 1$, and the information code element is defined as u. Then

$$u = [u(0) \quad u(1) \quad \ldots \quad u(k_b - 1)] \tag{4}$$

where each element in u is a $z \times 1$ column vector.

Check code element v is composed of m_b vectors of $z \times 1$.

$$v = [v(0) \quad v(1) \quad \ldots \quad v(m_b - 1)] \tag{5}$$

The process of encoding can be divided into two steps:

(a) Initialize and compute v (0);
(b) Recursively compute v $(i + 1)$ from v (i), where $0 \leq i \leq m_b - 2$.

Based on the above basic matrix H, each row of the basic matrix is summed and re-accumulated to obtain v (0), as shown below.

$$P_{p(x,k_b)}v(0) = \sum_{j=0}^{k_b-1}\sum_{i=0}^{m_b-1} P_{p(i,j)}u(j) \tag{6}$$

where x, $1 \leq x \leq m_b - 2$ is the number of rows of non-zero term of the basic matrix H. P_i denotes a cyclic right shift of i bits for a unit matrix of $z \times z$. There is

$$v(0) = P^{-1}_{p(x,k_b)}\left(\sum_{j=0}^{k_b-1}\sum_{i=0}^{m_b-1} P_{p(i,j)}u(j)\right) \tag{7}$$

And because P_i denotes the cyclic right shift of the unit matrix of $z \times z$ by i bits, $P^{-1}_{p(x,k_b)} = P_{z-p(x,k_b)}$.

The expression for $v(i)$ can be obtained by summing each row of the basic matrix, where $1 \leq i \leq m_b - 1$.

$$v(1) = \sum_{j=0}^{\mathrm{k}_b-1} P_{p(i,j)}u(j) + P_{p(i,k_b)}v(0), i = 0 \tag{8}$$

$$v(i+1) = v(i) + \sum_{j=0}^{\mathrm{k}_b-1} P_{p(i,j)}u(j) + P_{p(i,k_b)}v(0), i = 1, m_b - 2 \tag{9}$$

where, when $i = -1$, $P_i = 0_{z\times z}$.

2.3. LDPC Decoding Algorithm

The belief propagation (BP) decoding algorithm is an iterative algorithm for LDPC decoding, which effectively refines the estimation of codeword bits by iteratively exchanging messages between variable and check nodes. This iterative process enables the algorithm to converge to reliable codeword estimates, even amidst noise or errors in the received data [17].

Secondly, BP decoding boasts low computational complexity, rendering it feasible for real-time applications in communication systems. Additionally, it harnesses the inherent redundancy within LDPC code structures to achieve high levels of error correction performance, closely approaching the theoretical Shannon limit. Furthermore, the versatility and adaptability of BP decoding allow for customization to suit specific system requirements and constraints. These collective benefits position BP decoding as a preferred method for LDPC code decoding across various modern communication systems. The following describes the step-by-step process of the BP decoding algorithm in detail [18].

Step 1: Initialization. Before starting the iteration, the code initializes the LLR (log-likelihood ratio) information from variable nodes to check nodes (LLRQ) and from check nodes to variable nodes (LLRR), as well as the received channel information. The LLR information is computed based on the received channel information and external information, which is initially set to zero.

Step 2: Message passing. Communication between variable nodes and check nodes. Based on the received codewords and extrinsic information from neighboring nodes, the log-likelihood ratio (LLR) is calculated, and then the external information of the nodes is updated according to the LLR calculation. For each variable node, the LLR of the transmitted bits is calculated based on the received codewords and the extrinsic information from neighboring checking nodes, and then the extrinsic information of the checking nodes is updated by taking into account the syndrome information and the previous extrinsic information from neighboring variable nodes.

Step 3: Check for convergence. After each iteration, the code checks whether the codewords have converged, either by comparing them with the previous codewords or by reaching the maximum number of iterations. If the decoding process has not converged, it continues iterating; otherwise, it proceeds to the next step.

Step 4: Decision. In accordance with the eventual extrinsic information, a decision is made for each bit of the decoded codewords. Based on the final LLR information, decisions are made for each bit to determine the final decoding result. In this step, the sign of the LLR values is compared to determine the value of each bit: if the LLR is negative, the decoded result is 1; otherwise, it is 0.

Step 5: Output. The final decoded codewords are the result of the BP decoding algorithm.

The BP decoding algorithm iteratively refines the estimation of the codeword bits by exchanging messages between variable nodes and check nodes. This iterative refinement process enables the algorithm to progressively converge towards a reliable estimate of the codewords, even when the received codewords are affected by noise or errors. Through this iterative exchange of messages, the algorithm effectively leverages the redundancy inherent in the LDPC code structure to improve the accuracy of the decoded information.

3. PM-DQPSK System and Simulation Results

The PM-DQPSK coherent optical transmission system is one of the commercialized solutions for high-speed data transmission. It combines the optical polarization multiplexing technique and multiple phase shift keying (MPSK) techniques and applies coherent detection and digital signal processing (DSP) techniques, thereby reducing the implementation complexity and improving the spectral efficiency and OSNR sensitivity. The coherent optical transmission system is constructed by the optical simulation software VPItransmissionMaker10.1, and the digital signal processing compensation is carried out by MATLAB; the performance results before and after implementing LDPC encoding and decoding are compared in this paper.

3.1. PM-DQPSK Coherent Optical Transmission System

The theoretical model of the PM-DQPSK coherent optical transmission system is shown in Figure 1. The system comprises three main parts: the transmitter, the fiber link, and the receiver.

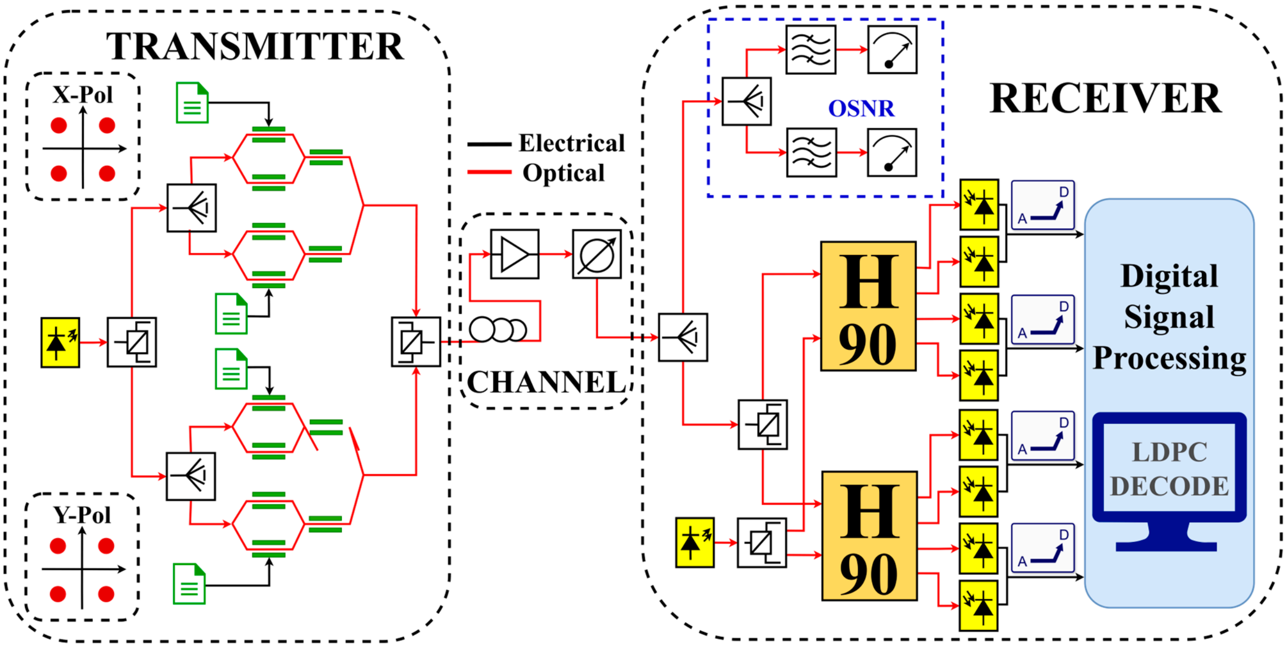

Figure 1. PM-DQPSK theoretical modeling of coherent optical transmission system.

The optical transmitter is responsible for the conversion of electrical signals to optical signals and includes various components such as lasers, modulators, and interfaces. Fiber optic transmission links are part of an optical fiber communication system used to establish point-to-point data connections [19]. Among them, noise accumulation, chromatic dispersion (CD), polarization mode dispersion (PMD), and nonlinear effects are common signal impairments during optical fiber transmission, which will cause interference to the transmitted optical signals and affect the performance of the optical fiber transmission systems. Therefore, mitigating these effects is crucial to ensure reliable and high-quality data transmission.

The fiber link represents the optical fiber channel through which the encoded signals propagate. This includes the physical fiber medium as well as any optical amplifiers or dispersion compensation devices along the transmission path [20]. The fiber link introduces various impairments, such as attenuation, dispersion, and nonlinear effects, which can degrade the quality of the transmitted signals.

The noise in a high-capacity long-distance transmission system mainly originates from the semiconductor optical amplifier (SOA), and the magnitude of its noise can be evaluated by the OSNR [21]. When an optical signal passes through the SOA, it not only amplifies the signal and its inherent noise but also introduces extra amplified spontaneous emission (ASE) noise. It is impossible to completely eliminate noise, so ensuring that certain OSNR at the receiver becomes crucial for effective transmission within the optical system. The noise figure (NF) serves as a metric for quantifying the extra noise introduced by a given system or device during the transmission of a signal. Essentially, it indicates the extent to which the system or device contributes additional noise to the transmitted signal. A lower NF signifies that the system or device introduces less supplementary noise during signal transmission, thus minimizing the degradation of signal quality. Consequently, a lower NF typically correlates with a higher OSNR, reflecting improved signal integrity and a more favorable transmission environment.

The optical receiver plays a crucial role in converting optical signals into electrical signals. This conversion is achieved through the utilization of a photodetector. The optical signals, transmitted via the optical fiber link, are received by the photodetector and transformed into electrical signals [22]. Initially, the electrical signal generated by the photodetector is relatively weak. An amplifier is employed to amplify the signal to an appropriate level. This amplification process ensures that the signal is robust enough for further processing. Once amplified, the electrical signal is forwarded to the DSP module.

Overall, the PM-DQPSK coherent optical transmission system employs sophisticated modulation and detection techniques to achieve high-speed and robust data transmission over long distances. Each component plays a crucial role in ensuring the fidelity and reliability of the transmitted information across the fiber link.

3.2. Digital Signal Processing Algorithms

At the receiving end of a coherent optical communication system, an analog-to-digital converter (ADC) is utilized to sample and quantize the electrical signals representing the in-phase (I) and quadrature (Q) components of each polarized light. This process results in the generation of four discrete digital sequences, which are then fed into a DSP unit for further processing.

Specifically, the ADC operation results in the generation of four discrete digital sequences corresponding to the I and Q components of both the X and Y polarizations. These digital sequences capture the amplitude and phase information of the received optical signals, enabling subsequent signal processing and data recovery.

Following ADC conversion, the digital sequences are fed into a DSP unit for further processing. The DSP unit performs various functions to enhance signal quality, mitigate impairments introduced during transmission, and extract the transmitted data accurately.

The compensation module of the PM-DQPSK signal transmission system is shown in Figure 2, which is crucial for maintaining the integrity of the transmitted signals and ensuring reliable communication performance.

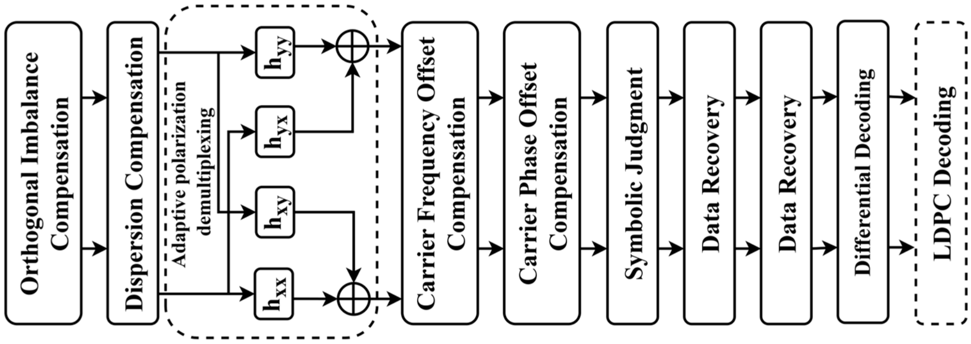

Figure 2. Digital signal processing compensation flowchart.

The compensation modules within the PM-DQPSK signal transmission system play a crucial role in enhancing the quality and reliability of the received signals, which can mitigate impairments and distortions that may occur during signal transmission [23]. Compensation techniques such as orthogonal imbalance compensation, dispersion compensation, chromatic dispersion compensation, polarization mode dispersion compensation, and nonlinear distortion mitigation are applied to enhance the signal quality and reliability, thereby contributing to the overall performance of the communication system. Below is a detailed description of the compensation process:

Firstly, the sampled signal is processed using the Gram–Schmidt orthogonalization procedure (GSOP). This procedure is utilized to orthogonalize the received signals, reducing interference and improving signal quality [24]. Subsequently, fixed dispersion coarse equalization techniques are applied to compensate for dispersion effects introduced during transmission. These techniques aim to mitigate signal distortions caused by dispersion, ensuring the integrity of the transmitted data [25]. Adaptive polarization demultiplexing algorithms are employed to separate and recover the original polarization states of the transmitted signals. This process is crucial for correctly decoding the data encoded in different polarization states [26]. And carrier frequency estimation compensation techniques are applied to estimate and correct any deviations in the carrier frequency of the received signals; this ensures accurate demodulation and recovery of the transmitted data [27]. Carrier phase estimation compensation techniques are utilized to estimate and compensate for variations in the carrier phase of the received signals. This step is essential for aligning the phases of the received signals with the reference phase, facilitating accurate demodulation [28]. Finally, the four discrete digital sequences generated by the compensation processes are sent to the symbol judgment module, which recovers the original valid data of the PM-DQPSK signal and allows for further data analysis or transmission.

3.3. Simulation Results

In this paper, following the compensation module mentioned above, LDPC is integrated into the PM-DQPSK coherent optical transmission system. Specifically, the LDPC decoding algorithm further processes the recovered data obtained from the symbol judgment module, enhancing the overall performance of the system.

The primary aim is to evaluate the effectiveness of LDPC in improving the quality and reliability of the transmitted data. Through a comparative analysis, the results from the comparison provide significant findings regarding the benefits and potential improvements that LDPC can provide in the PM-DQPSK coherent optical transmission system. This study seeks to elucidate the benefits and potential enhancements LDPC can provide within the context of the PM-DQPSK coherent optical transmission system.

To facilitate this evaluation, the parameters of the PM-DQPSK simulation system are configured as follows in Table 1.

Table 1. Parameters setting of PM-DQPSK simulation system.

Parameters	Value
Length of fiber	100 km
Transmission rate	40 Gbps
Output average power	1.0×10^{-3} W
Laser linewidth	100 kHz
PMD coefficient	0.2 ps/km$^{1/2}$
CD coefficient	16 ps/nm/km
Attenuation coefficient	0.2 dB/km
Effective core area	80.0×10^{-12} m^2
Semiconductor Optical Amplifier gain	20 dB

The system incorporates LDPC codes based on the IEEE802.16e standard, employing both the fast iterative coding algorithm and the BP decoding algorithm. These elements play pivotal roles in ensuring robust data transmission and error correction. Detailed parameter settings can be found in Table 2.

Table 2. LDPC parameter settings.

Parameters	Value
Coding lengths	576/1152/2304
Coding rate	1/2
Number of encodings	800/400/200
Maximum number of iterations	5/10/15/20

In order to ensure the effectiveness of the simulation, the control variables were carried out. Firstly, the different maximum numbers of iterations were changed for simulation, and the influence of different maximum numbers of iterations on error correction performance was compared. When adjusting the number of iterations, the LDPC configurations maintained consistent code length, code rate and number of encodings. Upon determining the optimal maximum number of iterations, simulations were conducted using LDPC codes of various lengths as specified in the IEEE802.16e standard. Specifically, the number of encodings corresponding to code lengths of 576, 1152, and 2304 are 800, 400, and 200.

The noise figure (NF) and OSNR are intimately related parameters in optical communication systems, particularly in receiver performance evaluation. NF quantifies the degradation of the OSNR introduced by electronic devices like amplifiers or receivers, with lower values indicating less noise contribution and better receiver sensitivity. On the other hand, OSNR measures the ratio of optical signal power to noise power in the system, reflecting signal quality relative to noise. There exists an inverse relationship between NF and OSNR: lower NF corresponds to higher sensitivity and improved OSNR, while higher NF results in decreased sensitivity and reduced OSNR. Adjusting the NF to manipulate the OSNR simulates attenuation damage and obtains different BER.

BP iterative decoding algorithm makes LDPC codes exhibit excellent performance. The decoding performance of LDPC code is affected by the number of iterations. When the number of iterations is small, the decoding information is still in unstable bagging, so it is necessary to increase the number of iterations, constantly accumulate more information, and improve the accuracy of the decoded message. The performance of the LDPC algorithm is assessed across various iteration counts. This paper selects 5, 10, 15, and 20 iterations for BER simulation analysis. As illustrated in Figure 3, the findings demonstrate an enhancement in decoding performance with an increase in the number of iterations.

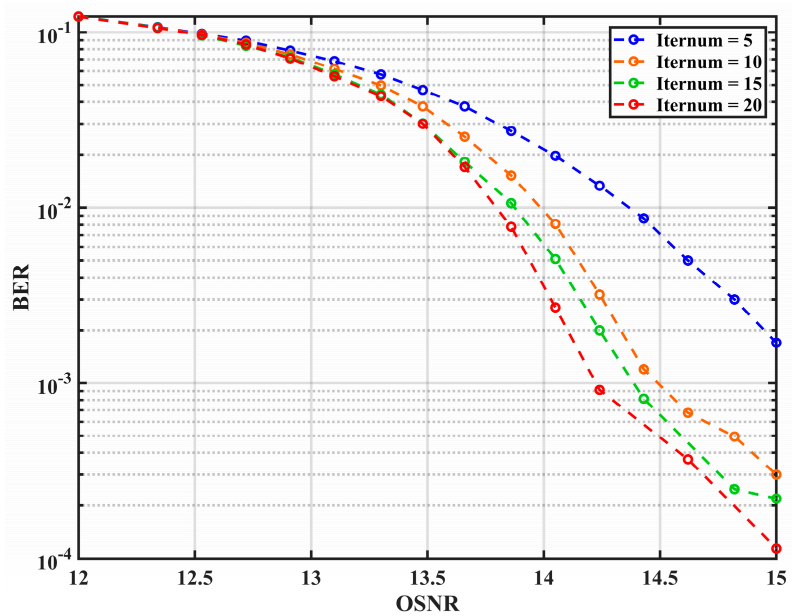

Figure 3. BER curve of the system with different maximum number of iterations.

The constellation changes in the polarization states of the PM-DQPSK signal during the distortion compensation process are illustrated in Figure 4. Specifically, Figure 4a,b illustrate the constellation diagrams of the X and Y polarizations, respectively, without any digital signal processing applied at the receiving end of the system. Subsequently, after undergoing damage compensation treatment, although some improvements in the constellation diagrams of the X and Y polarizations can be observed in Figure 4c,d, the constellation diagrams still have a certain degree of distortion, indicating that further optimization may be required to achieve satisfactory performance.

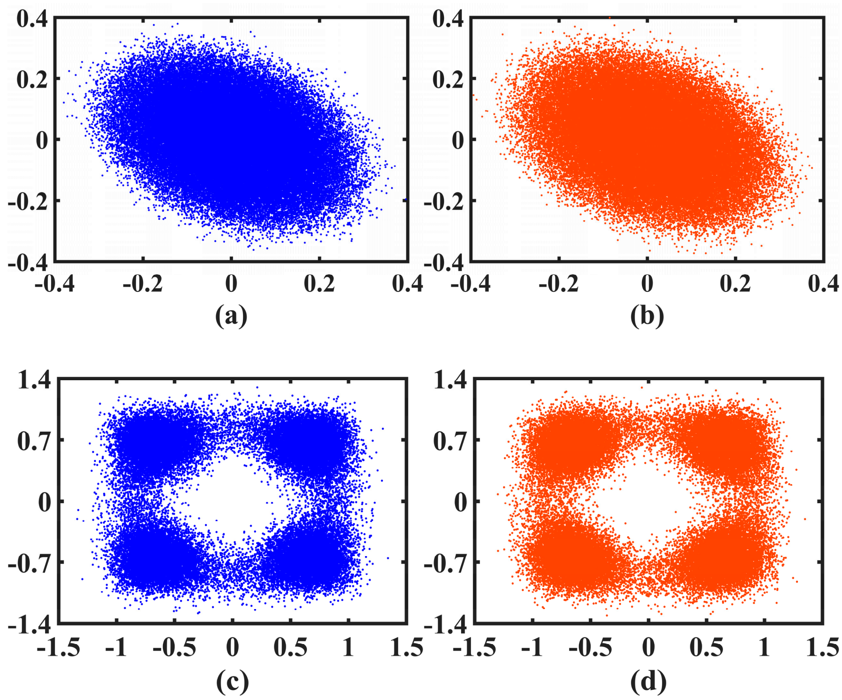

Figure 4. The constellations of X and Y polarization when OSNR = 15 dB: (**a**,**b**) receiver-received signal; (**c**,**d**) compensated but without LDPC.

By comparing the BER of the PM-DQPSK signal with and without the implementation of LDPC, the effectiveness of LDPC in reducing errors and enhancing the quality of the received signal can be evaluated. This comparative analysis provides valuable, significant results regarding the impact of LDPC on error reduction and signal quality improvement in the PM-DQPSK communication system.

Figure 5 demonstrates the BER plotted against different OSNR for a code rate of 1/2 and code lengths of 576, 1152, and 2304, each with 20 iterations. The results illustrate that incorporating LDPC significantly enhances the performance of the PM-DQPSK system across different OSNR values and code lengths.

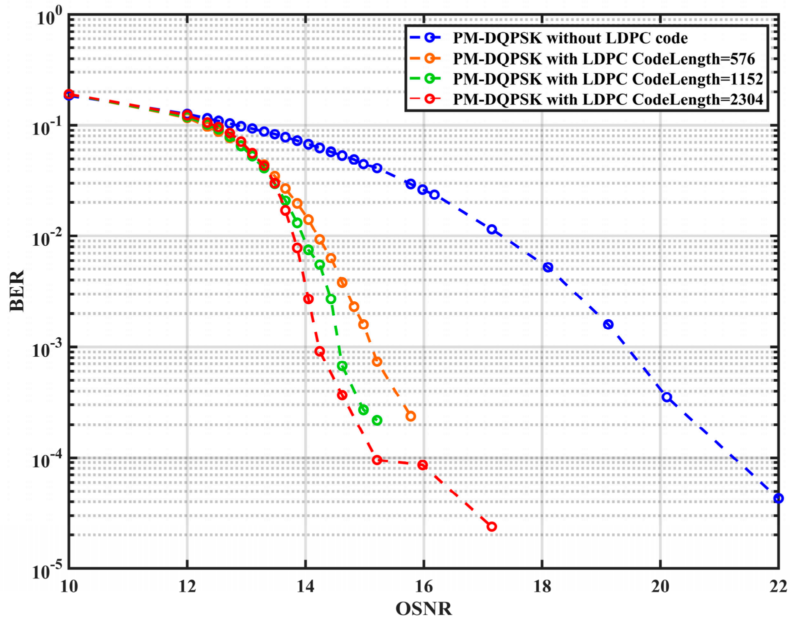

Figure 5. Coding gain and BER curve of PM-DQPSK system without and with different codelengths LDPC.

The LDPC coding gain is observed to approach approximately 4.3 dB, 5.1 dB, and 6 dB when the OSNR is 15 dB for code lengths of 576, 1152, and 2304. This indicates the improvement in signal quality achieved by LDPC coding under these conditions. Respectively, the BER is reduced by nearly three orders of magnitude when the OSNR is 17.2 dB. These findings underscore the remarkable effectiveness of LDPC in improving the reliability of the PM-DQPSK system, particularly in scenarios with challenging noise conditions.

4. Summary

This paper provides an overview of the IEEE802.16e LDPC code, including the construction of its H-matrix, the fast iterative coding algorithm, and the BP decoding algorithm. Additionally, it describes the PM-DQPSK coherent optical transmission system and explores the application of LDPC within this system. By comparing the performance of the system before and after the integration of LDPC encoding, the benefits and effectiveness of LDPC in the optical communication domain are verified. In subsequent steps, LDPC with modified code rate or other compilation algorithms can be applied in coherent optical transmission systems for further evaluation and comparison. These variations will help to study the effects of different LDPC parameters or configurations on system performance, thus deepening the understanding of the adaptability and utility of LDPC in optical communication systems. The incorporation of LDPC technology into coherent optical transmission systems significantly enhances the performance and reliability of modern optical communication systems across diverse applications and environments.

Author Contributions: Writing—original draft preparation, J.X.; writing—review and editing, Y.L.; conceptualization, J.X. and Y.Z. (Yichao Zhang); methodology, J.X. and X.W.; software, J.X. and Y.Z.

(Yichao Zhang); visualization, Y.Z. (Yanyue Zhang); supervision, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the National Natural Science Foundation of China under Grant 61901301.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ibrahimov, B.G.; Hasanov, M.H.; Tagiyev, A.D. Research of the Quality of Functioning of Fiber-Optical Transmission Systems on the Basis of Modern Technologies. In Proceedings of the 2022 Systems of Signals Generating and Processing in the Field of on Board Communications, Moscow, Russian, 15–17 March 2022; pp. 1–5.
2. Vyukusenge, A.; Rabenandrasana, J. Polarization Mode Dispersion Effects on Signal Quality and Compensation Methods. In Proceedings of the 2020 Systems of Signals Generating and Processing in the Field of on Board Communications, Moscow, Russia, 19–20 March 2020; pp. 1–6.
3. Hasanov, M.H. Research Indicators Nonlinear Effects in Fiber Optic Communication Lines in Use WDM and DWDM Technologies. In Proceedings of the 2021 Systems of Signals Generating and Processing in the Field of on Board Communications, Moscow, Russia, 16–18 March 2021; pp. 1–5.
4. Siddiqui, A.; Memon, K.A.; Hussain Mohammadani, K.; Memon, S.; Hussain, M.; Abbas, M. High Order Dual Polarization Modulation Formats for Coherent Optical Systems. In Proceedings of the IEEE 11th International Conference on Electronics Information and Emergency Communication (ICEIEC), Beijing, China, 18–20 June 2021; pp. 79–82.
5. Gallager, R. Low-density parity-check codes. *IRE Trans. Inf. Theory* **1962**, *8*, 21–28. [CrossRef]
6. Tanner, R.M. A recursive approach to low complexity codes. *IEEE Trans. Inf. Theory* **1981**, *27*, 533–547. [CrossRef]
7. Davey, M.C.; Mackay, D. Low-density parity check codes over GF(q). *IEEE Commun. Lett.* **1998**, *2*, 165–167. [CrossRef]
8. Richardson, T.; Urbanke, R. The renaissance of Gallager's low-density parity-check codes. *IEEE Commun. Mag.* **2003**, *41*, 126–131. [CrossRef]
9. Setyowati, E.; Suranegara, G.M.; Fauzi, A. Performance analysis of 16-QAM and 64-QAM with low density parity check code on wireless communication systems. *AIP Conf. Proc.* **2023**, *2734*, 060006.
10. Cuc, A.M.; Morgoş, F.L.; Grava, C. Performances Analysis of Turbo Codes, LDPC Codes and Polar Codes using AWGN channel with and without Inter Symbol Interference. In Proceedings of the 2022 International Symposium on Electronics and Telecommunications (ISETC), Timisoara, Romania, 10–11 November 2022; pp. 1–4.
11. Dehghan, A.; Banihashemi, A.H. On the Tanner Graph Cycle Distribution of Random LDPC, Random Protograph-Based LDPC, and Random Quasi-Cyclic LDPC Code Ensembles. *IEEE Trans. Inf. Theory* **2018**, *64*, 4438–4451. [CrossRef]
12. Zhu, K.; Wu, Z. Comprehensive Study on CC-LDPC, BC-LDPC and Polar Code. In Proceedings of the 2020 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), Seoul, Republic of Korea, 6–9 April 2020; pp. 1–6.
13. Schmalen, L.; ten Brink, S.; Leven, A. Advances in detection and error correction for coherent optical communications: Regular, irregular, and spatially coupled LDPC code designs. In *Enabling Technologies for High Spectral-Efficiency Coherent Optical Communication Networks*; Wiley: Hoboken, NJ, USA, 2016; pp. 65–122.
14. Mei, Z.; Cai, K.; Song, G. Performance Analysis of Finite-Length LDPC Codes Over Asymmetric Memoryless Channels. *IEEE Trans. Veh. Technol.* **2019**, *68*, 11338–11342. [CrossRef]
15. Degardin, V.; Lienard, M.; Zeddam, A.; Gauthier, F.; Degauquel, P. Classification and characterization of impulsive noise on indoor powerline used for data communications. *IEEE Trans. Consum. Electron.* **2002**, *48*, 913–918. [CrossRef]
16. Wang, Z.; Liu, B. Research on encoding and decoding algorithms of non-binary LDPC code and FPGA implementation. *J. Comput. Methods Sci. Eng.* **2020**, *20*, 167–175. [CrossRef]
17. Vatta, F.; Soranzo, A.; Babich, F. More Accurate Analysis of Sum-Product Decoding of LDPC Codes Using a Gaussian Approximation. *IEEE Commun. Lett.* **2019**, *23*, 230–233. [CrossRef]
18. Chang, T.C.Y.; Wang, P.H.; Weng, J.J. Belief-Propagation Decoding of LDPC Codes with Variable Node–Centric Dynamic Schedules. *IEEE Trans. Commun.* **2021**, *69*, 5014–5027. [CrossRef]
19. Winzer, P.J.; Neilson, D.T.; Chraplyvy, A.R. Fiber-optic transmission and networking: The previous 20 and the next 20 years. *Opt. Express* **2018**, *26*, 24190–24239. [CrossRef] [PubMed]
20. Yang, H.; Niu, Z.; Xiao, S. Fast and Accurate Optical Fiber Channel Modeling Using Generative Adversarial Network. *J. Light. Technol.* **2021**, *39*, 1322–1333. [CrossRef]
21. Wang, Z.; Shang, J.; Li, S.; Mu, K.; Yu, S. All-Polarization Maintaining Single-Longitudinal-Mode Fiber Laser with Ultra-High OSNR, Sub-kHz Linewidth and Extremely High Stability. *Opt. Laser Technol.* **2021**, *141*, 107135. [CrossRef]
22. Amiri, I.S.; Mohammed Aref Mahmoud Houssien, F.; Rashed, A.N.Z.; Mohammed, A.E.N.A. Optical Networks Performance Optimization Based on Hybrid Configurations of Optical Fiber Amplifiers and Optical Receivers. *J. Opt. Commun.* **2019**. [CrossRef]
23. Zhao, J.; Liu, Y.; Xu, T. Advanced DSP for coherent optical fiber communication. *Appl. Sci.* **2019**, *9*, 4192. [CrossRef]

24. Mahendra, R.; Mohammed, S.K.; Mallik, R.K. Compensation of Transmitter IQ Imbalance in Multi-User Hybrid Beamforming Systems. *IEEE Access* **2021**, *9*, 98231–98248. [CrossRef]
25. Yang, J.; Liu, H.; Wang, J. Research on dispersion equalization technology in coherent optical communication. *Second. Int. Conf. Electron. Inf. Technol.* **2023**, *12719*, 532–537.
26. Du, Q.; Zhang, X.; Guo, Y. Density-matrix-formalism based scheme for polarization mode dispersion monitoring and compensation in optical fiber communication systems. *Optoelectron. Lett.* **2023**, *19*, 739–743. [CrossRef]
27. Tan, Q.; Yang, A.; Guo, P.; Zhao, Z. Blind frequency offset estimation based on phase rotation for coherent transceiver. *IEEE Photonics J.* **2020**, *12*, 7902212. [CrossRef]
28. Jin, C.; Shevchenko, N.A.; Li, Z.; Popov, S.; Chen, Y. Nonlinear coherent optical systems in the presence of equalization enhanced phase noise. *J. Light. Technol.* **2021**, *39*, 4646–4653. [CrossRef]