Polarization Division Multiplexing Coherent Optical OF DM Transmission Systems

Ali Y. Fattah[1], Falah Hasan Abdul-Baqi[2]

[1,2]Department of Electrical Engineering, University of Technology – Baghdad

Email: dralifattah@yahho.com, falahhassan2012@gmail.com

Received: 16/2 /2014

Accepted: 11/11 /2015

Abstract –High-capacity and long-haul transmission technologies are indispensable to develop cost-effective optical transport networks. Optical communication is rapidly advancing toward 1-Tera bit per second (Tb/s) and beyond transport. As the available bandwidth of Standard Single-Mode Fiber (SSMF) is limited, high Spectral Efficiency (SE) becomes an important issue. Coherent Optical Orthogonal Frequency-Division Multiplexing (CO-OFDM) has become one of the promising candidates due to its high SE and resilience to linear channel impairments such as Chromatic Dispersion (CD). In this paper, based on Optisystem 11.0 software simulation platform, the performance of a 1.6 Tb/s (16 x 100 Gb/s) PDM-CO-OFDM transmission system is investigated invest by using QPSK modulation format and applying Polarization Interleaving Scheme (PIS) over 1440 km with 2 b/s/Hz spectral efficiency.

Keywords – Polarization Division Multiplexing (PDM), Coherent Optical Orthogonal Frequency-Division Multiplexing CO-OFDM, Quadrature Phase Shift Keying (QPSK), Polarization Interleaving Scheme (PIS), Optisystem.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is an attractive modulation format that recently received a lot of attention in the fibre-optic community [1]. OFDM is a multicarrier transmission technique where a data stream is carried with many lower-rate subcarrier tones. OFDM has received increased attention as a mean to overcome various limitations of optical transmission systems such as modal dispersion, relative intensity noise, chromatic dispersion, polarization mode dispersion and self-phase modulation [2].

The ever-increasing demand on capacity due to emerging internet applications has led to an intensive study of high spectral-efficiency (SE) and high data rate transport for optical networks. It has been demonstrated very recently that a data rate of 1 Tb/s and beyond can be achieved in a coherent optical orthogonal frequency-division multiplexing (CO-OFDM) [3]. CO-OFDM combines the advantages of "coherent detection" and "OFDM modulation" and possesses many merits that are critical for future high-speed fibre transmission systems [4]. Previous experiments have shown that CO-OFDM has the advantage of high SE and resilience to the linear channel impairments such as chromatic dispersion [3]. Independent of the utilized transmission scheme, the overall SE is defined as the ratio of net bit rate per wavelength-division multiplexing (WDM) channel to WDM channel spacing, and for the case that coherent optical orthogonal frequency-division multiplexing (CO-OFDM) is used, the intrachannel spectral efficiency (ISE) is calculated as the ratio between the net bit rate per subcarrier and the subcarrier spacing [5, 6]. The ISE constitutes a usually tightly achievable upper bound on the SE for WDM operation, i.e., ISE ≥ SE [7].

The use of Polarization Division Multiplexing (PDM) permits to multiply the user capacity and to increase the spectral efficiency. Combining PDM and OFDM modulation allows maximizing the optical transmission capacity. Ongoing commercial developments with WDM of 100-Gb/s channels on a 50-GHz channel grid consider the PDM-CO-OFDM system as the most suitable modulation format force for higher spectral efficiency (SE) in long-haul optical transmission system [7].

A Polarization Interleaving Scheme (PIS) is used in the designing of the WDM system to reduce the effects of the nonlinear impairments and the crosstalk especially at low channel spacing [8].

In this paper, based on Optisystem 11.0 software package, the performance of a 1.6 Tb/s (16 x 100 Gb/s) PDM-CO-OFDM transmission system is investigated by using QPSK modulation format and applying PIS over 1440 km with 2 b/s/Hz spectral efficiency. In this study It is shown that the BER sensitivity performance of the center channel = 193.1 THz, to achieve OSNR for a BER of 10^{-3} is 19.9 dB, and the maximum Q factor is 11.7 dB at optimal input power = -1 dBm.

2. OFDM Basics

OFDM is a multicarrier transmission technique based on the Fast Fourier transform (FFT), where a data stream is divided into several low bit rates streams that are simultaneously modulated onto orthogonal subcarriers, see Figure 1. The OFDM modulation scheme also leads to a high spectral efficiency because of its partially overlapping subcarriers. Moreover, the cyclic prefix code of the OFDM system makes the system more resistant to Inter-Symbol Interference (ISI) caused by Chromatic Dispersion

(CD) and Polarization Mode Dispersion (PMD).

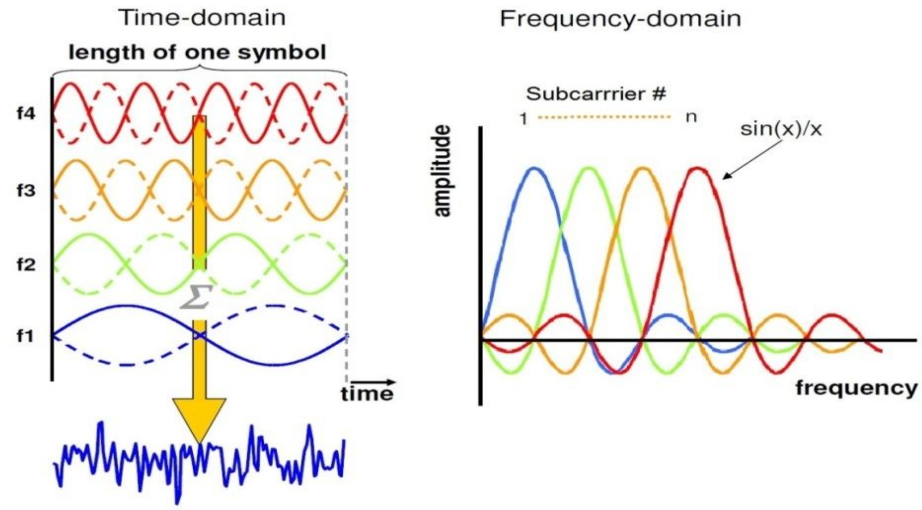

Figure (1) OFDM subcarriers waveform [9]

In a multi-carrier modulation system (MCM), the data stream is parsed into several parallel sub-streams and each sub-stream modulates one subcarrier. The MCM transmitted signal $s(t)$ is represented as [10], [11],

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{SC}} c_{\mathrm{ki}}\, s_{\mathrm{k}}(t - iT_{\mathrm{s}}) \quad (1)$$

$$s_{\mathrm{k}}(t) = \prod(t)\, \mathrm{e}^{\mathrm{j}2\pi f_{\mathrm{k}}\mathrm{t}} \quad (2)$$

$$\prod(t) = \begin{cases} 1, & (0 < t \leq T_{\mathrm{s}}) \\ 0, & (t \leq 0, t > T_{\mathrm{s}}) \end{cases} \quad (3)$$

where c_{ki} is the ith information symbol at the k^{th} subcarrier, s_{k} is the waveform for the k^{th} subcarrier, N_{SC} is the number of subcarriers, f_{k} is the frequency of the subcarrier, and T_{s} is the symbol period, $\prod(t)$ is the pulse shaping function. If we sample $s(t)$ in "(1)," with sampling period of Ts/N, the m_{th} sample can be represented as,

$$s_{\mathrm{m}} = \sum_{k=1}^{N} c_{\mathrm{k}} \,.\, \mathrm{e}^{\mathrm{j}2\pi f_{\mathrm{k}}(\mathrm{m}-1)\mathrm{Ts}/\mathrm{N}} \quad (4)$$

In an OFDM system, different subcarrier carrier frequencies are chosen so that each subcarrier is orthogonal to each other. Because of the orthogonality of the OFDM subcarrier [10], [11],

$$f_k = \frac{(k-1)}{T_{\mathrm{S}}} \quad (5)$$

Substituting "(5)," into "(4)," we get "(6),"

$$s_{\mathrm{m}} = \sum_{k=1}^{N} c_{\mathrm{k}} \,.\, \mathrm{e}^{\mathrm{j}2\pi(\mathrm{m}-1)(\mathrm{k}-1)/\mathrm{N}} = \mathfrak{F}^{-1}\{c_{\mathrm{k}}\} \quad (6)$$

where $\mathfrak{F}$ is the Fourier transform, and m ∈ [1,N]. In a similar manner, at the receive end, we arrive at

$$\hat{c}_k = \frac{1}{\sqrt{N}} \sum_{k=1}^{N} \hat{s}_m \cdot e^{-j2\pi(m-1)(k-1)/N} = \mathfrak{F}\{r_m\} \qquad (7)$$

where r_m is the received signal sampled at every interval of Ts/N. From "(6)," and "(7),", it follows that the discrete value of the transmitted OFDM signal $s(t)$ is merely a simple N-point IDFT of the information symbol c_k, and the received information symbol $\hat{c}_k$ is a simple N-point DFT of the receive sampled signal.

In most OFDM systems, a Cyclic Prefix (CP) is added to the start of each time domain OFDM symbol before transmission [12], as shown in Figure 2. If the receiver FFT window is aligned with the start of the main symbol period of the first arriving signal and the delay spread, introduced into the system by the channel, is smaller than the CP, then no ISI occurs.

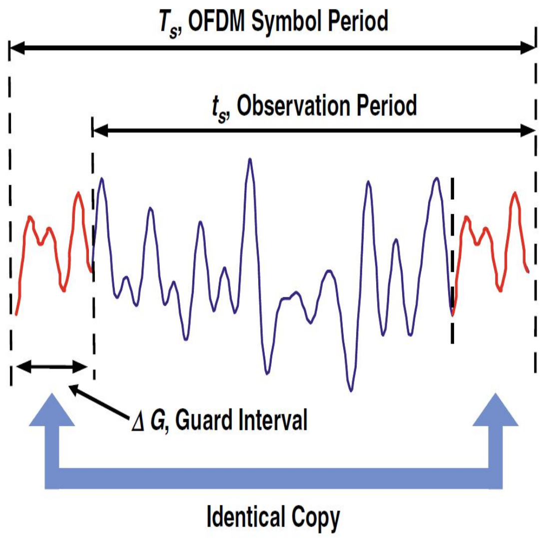

Figure (2) Time-domain OFDM signal for one complete OFDM symbol [11]

The signal is mapped in QPSK modulation format before doing the IFFT. The block diagram of the transmitter is shown in Figure 3, it is composed of Serial to Parallel (S/P) converter, a mapper, an IFFT of N points, and a block to insert the CP and a Parallel to Serial (P/S) converter. With the mapping, a certain number of bits are represented by each symbol. The IFFT block generates an OFDM symbol with N orthogonal subcarriers. The channel dispersion can destroy the orthogonally between subcarriers so the CP is added to combat the dispersion of the channel and avoid ISI [13].

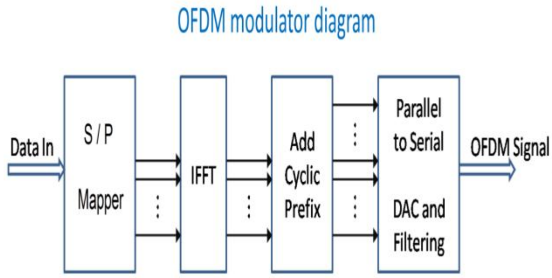

Figure (3) Block diagram of the OFDM transmitter based on the FFT

Moreover equalization is necessary to mitigate the effects of the channel such as dispersion that can lead to ISI, enhancing the performance of the system. Finally the resulting signal is serialized, digital-to-analog converted and it is sent through the channel.

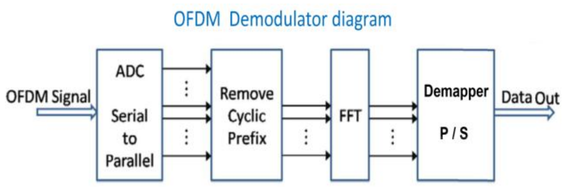

Figure (4) Block diagram of the OFDM receiver based on the FFT [13]

In the receiver, the inverse process takes place. Firstly, after the detection of the signal, the data is serial to parallel converted in order to remove the CP in the following step, see Fig. 4. Then the FFT is implemented and finally the resulting signal is de-mapped, serialized and analog-to-digital converted in order to recover the original bit stream [13]. The robustness against channel dispersion and its ease of phase and channel estimation in a time-varying environment make OFDM a suitable advanced modulation format for optical communications systems.

3. Principle for CO-OFDM System

Figure 5 shows the conceptual diagram of a typical coherent optical OFDM system setup. It contains five basic functional blocks: RF OFDM signal transmitter, RF to Optical (RTO) up-converter, Fiber links, the Optical to RF (OTR) down-converter, and the RF OFDM receiver [11].

The input data for the OFDM modulator can have different modulation formats such as BPSK, QPSK, QAM, etc. At the transmission block, both modulation and multiplexing are achieved digitally using an Inverse Fast Fourier Transform (IFFT).

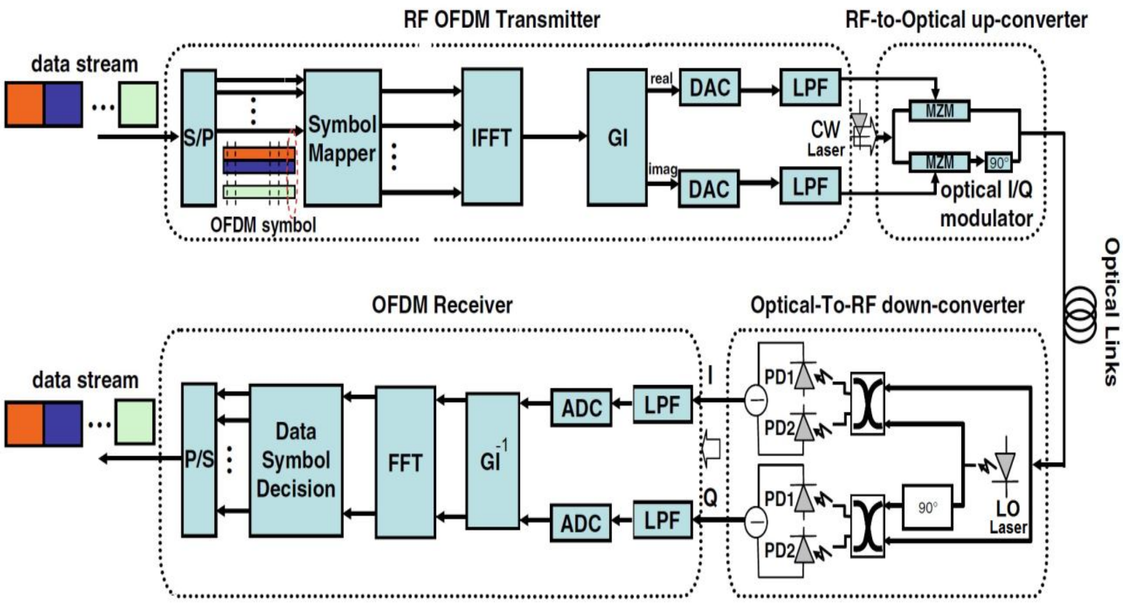

Figure (5) Conceptual diagram of a coherent optical OFDM system [11]

The subcarrier frequencies are mathematically orthogonal over one OFDM symbol period. A Continuous Wave (CW) laser and two Mach-Zehnder Modulators are used to up-convert the RF data to the optical domain. The signal is then propagated through the optical link and becomes degraded due to fiber impairments. A homodyne coherent receiver with a Local Oscillator (LO) is used to down-convert the data to the RF domain, and finally the data is demodulated and sent to the detector and decoder for BER measurements.

The time domain OFDM signal is obtained through Inverse Fast Fourier Transform (IFFT) of (c_{ki}), and a guard interval (Δ_{G}) is inserted to avoid channel dispersion. The resultant baseband time domain signal $s_{\mathrm{B}}(t)$ can be described as [10],

$$s_{\mathrm{B}}(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=-N_{SC}/2+1}^{k=N_{SC}/2} c_{\mathrm{ki}} \prod(t - iT_{\mathrm{s}})\, \mathrm{e}^{\mathrm{j}2\pi f_{\mathrm{k}}(t-iT_{\mathrm{s}})} \qquad (8)$$

$$f_k = \frac{k-1}{t_s} \quad (9)$$

$$\prod(t) = \begin{cases} 1, & (-\Delta_G < t \le t_s) \\ 0, & (t \le -\Delta_G, t > t_s) \end{cases} \quad (10)$$

where c_{ki} is the ith information symbol at the k^{th} subcarrier, f_k is the frequency of the k^{th} subcarrier, N_{SC} is the number of OFDM subcarriers, T_S, Δ_G, and t_s are the OFDM symbol period, guard interval length, and observation period, respectively, $\prod(t)$ is the rectangular pulse waveform of the OFDM symbol.

At the RTO up-converter, the baseband OFDM $S_B(t)$ signal is upshifted onto the optical domain using an optical I/Q modulator, which is comprised by two Mach–Zehnder modulators (MZMs) with a 90° optical phase shifter. The up-converted OFDM signal in optical domain is given by

$$E(t) = \exp(j\omega_{LD1}t + \emptyset_{LD1})\, S_B(t), \quad (11)$$

where ω_{LD1} and $\emptyset_{LD1}$ are the frequency and phase of the transmitter laser, respectively. The optical signal $E(t)$ is launched into the optical fiber link, with an impulse response of $h(t)$. The received optical signal $E'(t)$ becomes

$$E'(t) = \exp(j\omega_{LD1}t + \emptyset_{LD1})\, S_B(t) \otimes h(t) \quad (12)$$

where $\otimes$ stands for the convolution operation.

When the optical signal is fed into the OTR converter, the optical signal $E'(t)$ is then mixed with a local laser (LO) at a frequency of ω_{LD2} and a phase of $\emptyset_{LD2}$. Assume the frequency and phase difference between transmitter and receiver lasers are,

$$\Delta\omega = \omega_{LD1} - \omega_{LD2}, \quad \Delta\emptyset = \emptyset_{LD1} - \emptyset_{LD2} \quad (13)$$

Then the received RF OFDM signal $r(t)$ can be expressed as [10],

$$r(t) = \exp(j\Delta\omega t + \Delta\emptyset)\, S_B(t) \otimes h(t) \quad (14)$$

3.1. Optical Spectral Efficiency SE for CO-OFDM

In CO-OFDM systems, N_{SC} subcarriers are transmitted in every OFDM symbol period of T_S. Thus the total symbol rate R for CO-OFDM systems is given by [14]

$$R = N_{SC}/\ T_S \quad (15)$$

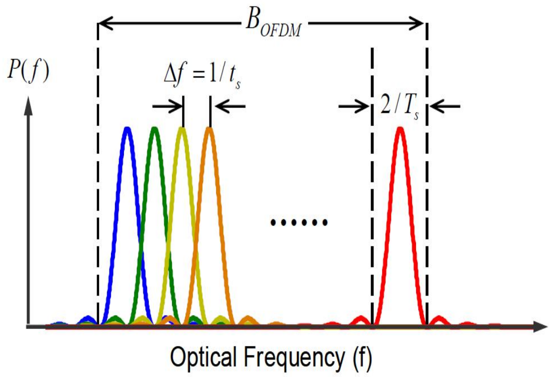

Figure (6) The optical spectrum of one WDM channel [14]

Figure 6 shows the spectrum of Wavelength-Division-Multiplexed WDM) channel. The bandwidth of the first null is used to denote the boundary of each wavelength channel. The OFDM bandwidth B_{OFDB} is thus given by:

$$B_{OFDB} = \frac{2}{T_S} + \frac{N_{SC}-1}{t_S} \quad (16)$$

where t_S is the observation period as shown in Fig. 2. Assuming a large number of subcarriers used, the bandwidth efficiency of OFDM η is,

$$\eta = 2\frac{R}{B_{OFDB}} = 2\alpha, \quad \alpha = \frac{t_S}{T_S} \quad (17)$$

The factor of 2 accounts for two polarizations in the fiber.

3.2. Optical Signal to Noise Ratio OSNR for CO-OFDM

The optical amplification process is accompanied by Amplified Spontaneous Emission (ASE) noise that accumulates along the transmission line, degrading the OSNR, defined by [15],

$$\text{OSNR} = \frac{P_S}{P_{ASE}} \quad (18)$$

Where P_S is the signal power, P_{ASE} is the noise power. The OSNR can be measured at the receiver entrance point (just before the photo detector). It is quite instructive to explicitly write out the ideal coherent detection performance for CO-OFDM systems where the line widths of the transmit/receive lasers are assumed to be zero. The corresponding BER, Q and OSNR in this ideal condition can be shown given by [15],

$$BER = 0.5 \cdot erfc\left(2\sqrt{2 \cdot OSNR \cdot \frac{B_0}{R}}\right) \quad (19)$$

$$Q = 10 \ \log_{10}\left(4 \cdot OSNR \cdot \frac{B_0}{R}\right) \quad (20)$$

where B_0 is the optical ASE noise bandwidth used for OSNR measurement (~12.5 GHz for 0.1 nm bandwidth),

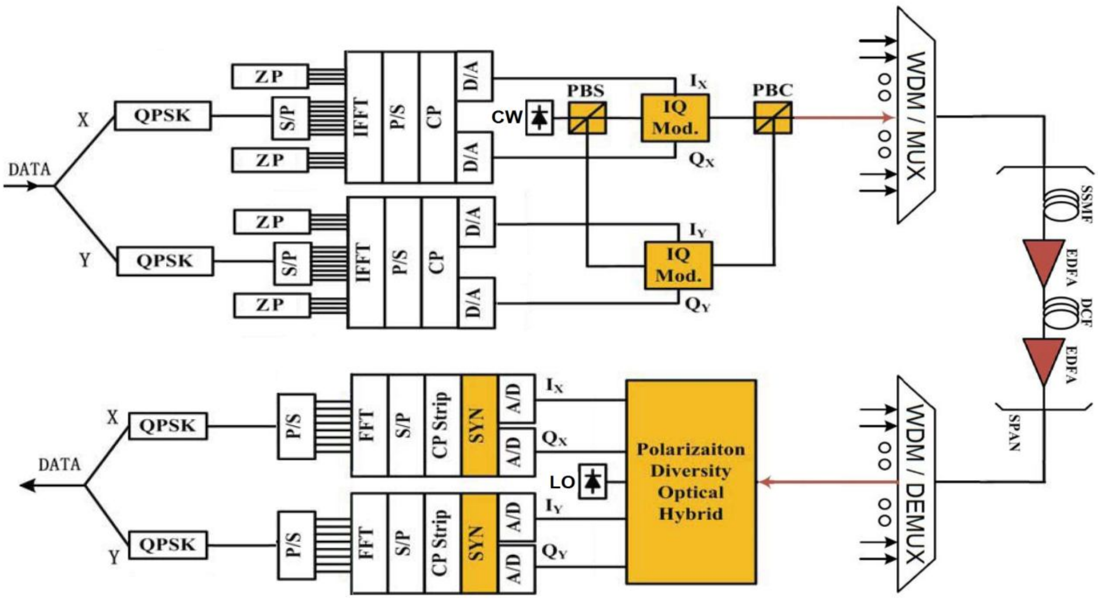

Figure (7) Conceptual diagram of the WDM PDM-CO-OFDM system

$R \equiv N_{SC}.\Delta f$ is the total system symbol transmission rate, N_{SC} and Δf are the number of the subcarriers and channel spacing of the subcarriers, respectively.

4. Polarization Division Multiplexing PDM CO-OFDM System

PDM-CO-OFDM system is a very effective method for doubling spectrum efficiency and the capacity (bit rate) of transmission system [16], [17]. AS shown in Figure 7, two independent baseband signals modulate the orthogonally polarized parts of the transmit laser signal. To achieve this, the signal of the CW laser source is split by a Polarization Beam Splitter (PBS). Next, two external optical I/Q-modulators are applied before both signal contributions are recombined by a Polarization Beam Combiner (PBC) and launched into the optical waveguide. At the receiver, polarization diverse coherent homodyne detection is deployed. Once again polarization beam splitters are required to provide orthogonally polarized contributions of the received signal as well as the LO laser to optical hybrids. Balanced photo-detectors then convert their outputs to electrical representations of the in phase and quadrature components of both orthogonal RX signals.

To avoid aliasing due to the sampling process of the digital-to-analog converter (DAC), Zero Padding (ZP) is needed. This shifts the aliases away from the OFDM signal. By inverse fast Fourier transformation (IFFT), one obtains the time-domain OFDM signal. The IFFT size determines the numbers of subcarriers and the numbers of ZP. The ZP may be inserted in the middle of the IFFT sequence or at its edges. Usually half of the input IFFT sequence is used for ZP while the other half is used for subcarriers because of the required Hermitian symmetry. The IFFT size usually lies between 128 [18] and 1024 [19]. Increasing the IFFT size makes the signal less susceptible to Iinter Symbol Interference (ISI) between OFDM symbols. Its drawbacks are the increased processing complexity at transmitter and receiver and the increased sensitivity to laser phase noise in case of coherent detection.

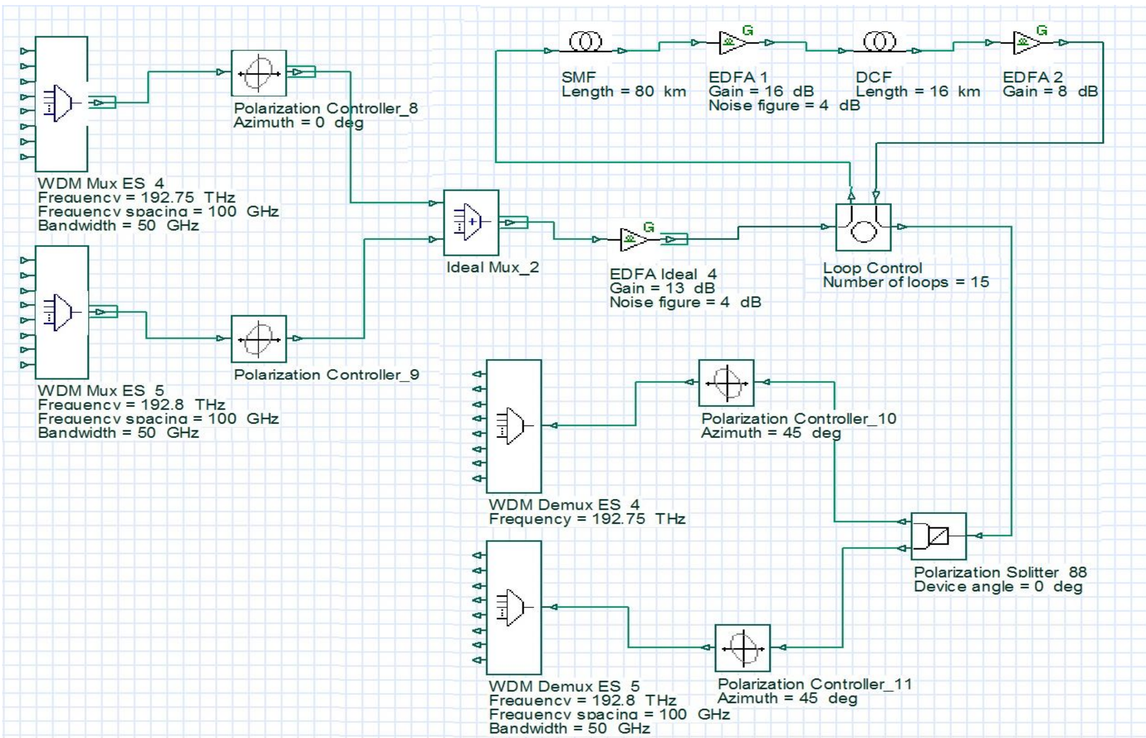

Figure (8) WDM systems (16 × 100 Gb/s PDM-CO-OFDM) applying PIS with 50 GHZ channel spacing

5. Polarization Interleaving Scheme

A polarization-interleaving scheme (PIS) is used in the designing of the WDM system to decrease the effects of SRS, XPM and FWM [8]. The State of Polarization (SOP) of the odd numbered channels is made 0^o while the (SOP) of the even numbered channels is made 90^o so that each channel is orthogonal with the channel beyond it. Figure 8 shows the investigated 1.6 Tb/s (16 x 100 Gb/s) PDM-CO-OFDM transmission system applying polarization interleaving scheme, with 50 GHz channel spacing, inline dispersion compensation.

Table 1. WDM (Mux, Demux) simulated parameters.

Parameter	Value
WDM Multiplexer and Demultiplexer	
Channel spacing	50 GHz
Bandwidth	100 GHz
Insertion loss	4 dB
Filter type	Guassian
Filter order	2

6. Simulation Setup

The 1.6 Tb/s (16 x 100 Gb/s) PDM-CO-OFDM transmission system applying PIS with inline dispersion compensation is setup by using a commercial fiber optics system simulation tool, OptiSystem™ 11.0, as shown in Figure 7. At the transmitter, the output of 16 CW lasers (0.1 MHz line width), aligned on a 50-GHz ITU grid between 192.75 THz and 193.5 THz, are modulated by using two parallel modulator structures for separate modulation of the even and odd channels. An OFDM signal with a data rate of 50 Gb/s is gnerated from a Pseudo Random Binary Sequence (PRBS) of length $2^{13}-1$. This bit stream was converted from serial to parallel, and then mapped with 4-QAM (QPSK) encoder. An IFFT/FFT size of 1024 is used with 512 OFDM subcarriers and 512 Zero Padding (ZP) at the edges of the IFFT. The 50 Gb/s rate OFDM in-phase and quadrature parts then pass the low pass filter. The Mach–Zehnder modulator is used to convert electrical signals to optical signals. A polarization-interleaving scheme is used in the designing of the WDM system, to decrease the effects of the nonlinear impairments and the crosstalk especially at low channel spacing, as shown in Fig. 8. WDM (Mux, Demux) simulated parameters of the (16 × 100 Gb/s) PDM-CO-OFDM system applying PIS listed in Table 1. The optical channel consists of 15 spans of 80 km Standard Single Mode Fiber (SSMF), with attenuation = 0.2 dB/km, dispersion (D) = 16 ps/nm-km and dispersion slope coefficient of 0.075 ps/ nm^2 -km with an effective area of 80 μm^2 and nonlinearity coefficient γ = 2.09 W^{-1} km^{-1}.

Fiber dispersion is fully compensated by the Dispersion Compensation Fiber (DCF) of 16 km in each span which has 0.5 dB/km attenuation, -80 ps/nm-km dispersion and, the dispersion slope coefficient is -0.3 ps/nm^2-km with an effective area of 22 μm^2 and nonlinearity coefficient γ = 6.4 W^{-1} km^{-1}. The simulation value of the Differential Group Delay (DGD) parameter for all the fiber types is 0.1 ps/$\sqrt{\text{km}}$. Both the SSMF and DCF span loss is balanced by two 4 dB noise figure optical amplifiers (EDFA's) in each loop with a gain value of 16 dB, 8 dB respectively. This configuration of the optical channel forms the post dispersion-compensating scheme. At the receiver, a homodyne detector is assumed. The 16 Local Oscillators (LO) laser are perfectly aligned on a 50-GHz ITU grid between 192.75 THz and 193.5 THz, and line width equals to 0.1 MHz. The I/Q components of the OFDM signal are recovered by a 2x4 90 degree optical hybrid and two pairs of photo-detectors. Photo-detector noise, such as thermal, shot noise, dark current and ASE noise are included in the simulation. The converted OFDM RF signal is demodulated by using FFT processor and the guarding interval is removed. The obtained signals are fed into a 4-QAM (QPSK) decoder. The reference bit rate parameter refers to the original bit rate of the transmitted digital signal, while the Delay Compensation (DC) parameter is used to synchronize the received signal. Transmission bits are collected and Bit Error Ratio (BER) is calculated for both the system and compared at the end of the receiver.

7. Simulation Result

The 1.6 Tb/s (16 x 100 Gb/s) PDM-CO-OFDM system applying PIS with inline dispersion compensation is investigated as shown in Fig. 6. Figure (9) shows allocation of OFDM subcarriers, the OFDM bandwidth B_{OFDB}= 25 GHz, channel spacing of the subcarriers Δf= 50 MHz.

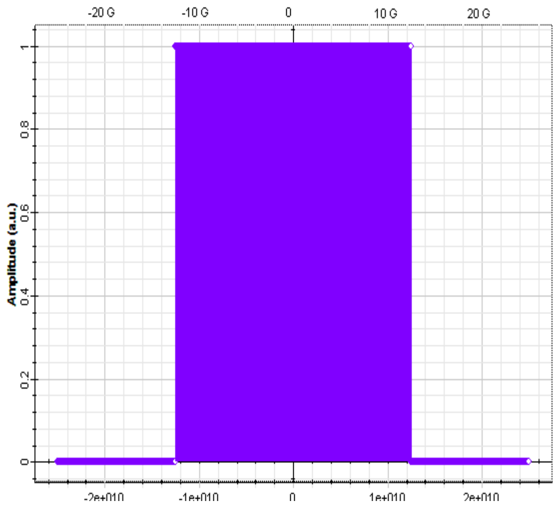

Figure (9) Allocation of OFDM subcarriers

RF spectrum and optical spectrum of transmitted and received signal for the center channel number 8 with carrier frequency = 193.1 THz, after 1440 km distance, are shown in Fig. 10 and Fig. 11 respectively. Figure (12) shows the optical spectrum of transmitted and received signal for (16 × 100 Gb/s) PDM-CO-OFDM transmission system, with 50 GHz channel spacing, applying PIS, after 1440 km distance, with inline dispersion compensation.

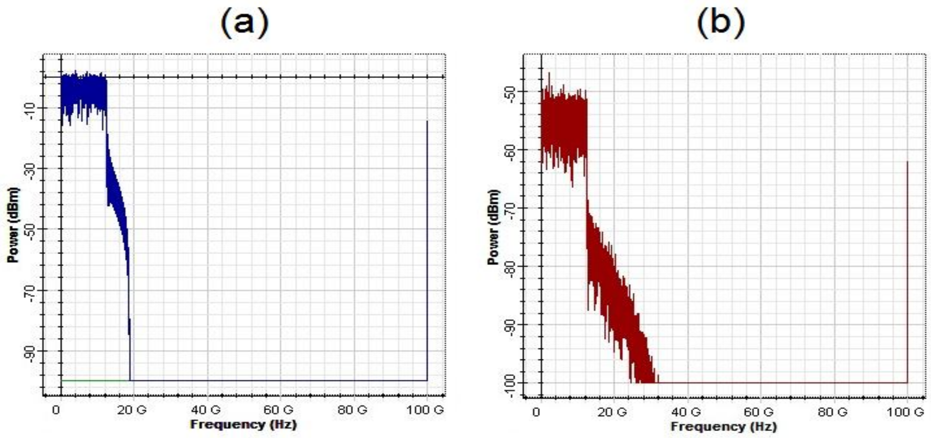

Figure (10) RF spectrum of (a) transmitted and (b) received signal

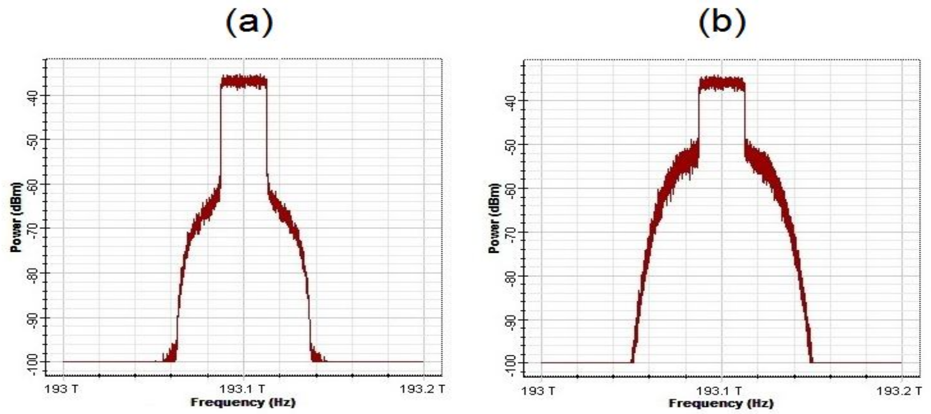

Figure (11) Optical spectrum of (a) transmitted and (b) received signal

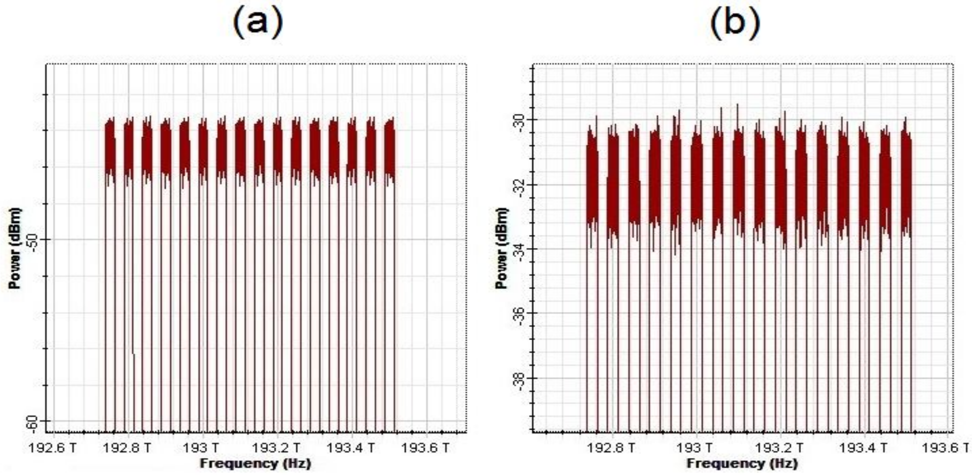

Figure (12) The optical spectrum of transmitted and received signal for 16 × 100 Gb/s PDM-CO-OFDM transmission system

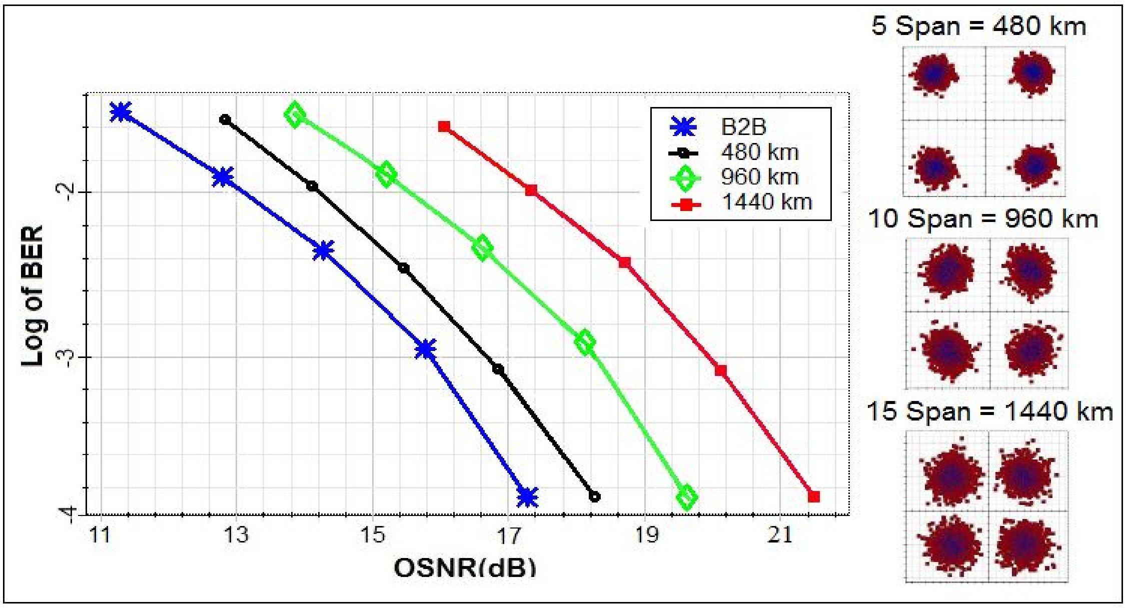

Figure (13) BER versus OSNR
Inset: Recovered constellation diagrams after 480, 960 and 1440 km.

Table (2): Required OSNR, Delay Compensation and Maximum Q Factor.

Transmission Distance	OSNR (dB) for BER = 10^{-3}	Delay Compensation		Max. Q Factor (dB)
		X Pol.	Y Pol.	
B2B	15.8	0 ns	0 ns	------
480 km	16.7	- 0.025 ns	- 0.025 ns	16.2
960 km	18.2	- 0.05 ns	- 0.05 ns	13.1
1440 km	19.9	- 0.07 ns	- 0.07 ns	11.7

Figure (13) shows BER versus OSNR of the center channel=193.1 THz, for the Back to Back (B2B), 480, 960 and 1440 km transmission distance**.** The inset shows the recovered signal constellation diagrams after 480, 960 and 1440 km distance, at optimal input power = -1 dBm. The required OSNR for BER $=10^{-3}$, Delay Compensation and Maximum Q Factor of the center channel=193.1 THz at optimal input power = -1 dBm are summarized in Table (2).

8. Conclusions

In this paper, the performance of 1.6 Tb/s (16 x 100 Gb/s) PDM-CO-OFDM transmission system with 50 GHz channel spacing by numerical simulation have been studied by using QPSK modulation format and applying PIS over 480 km, 960 km and 1440 km transmission distance with 2 b/s/Hz spectral efficiency. The results show that as the transmission distance increases, the nonlinear effects on the fiber link increases, and the required OSNR to maintain a BER in less than 10^{-3} increases. The BER sensitivity performance of the center channel = 193.1 THz, after 1440 km, to achieve OSNR for a BER of 10^{-3} is 19.9 dB, and the maximum Q factor is 11.7 dB at optimal input power = -1 dBm. In the future study of the system, high level modulation format for instance M-QAM (16-QAM, 64-QAM) will be used to increase spectral efficiency (SE), also the use of Mid-span Digital Phase Conjugation (DPC) to mitigate the nonlinear phase noise and increase the transmission distance.

References

[1] W. Shieh, "OFDM for Flexible High-Speed Optical Networks," IEEE J. Lightwave Technology, Vol. 29, No. 10, May. 2011.

[2] W. Shieh, H. Bao, and Y. Tang, "Coherent optical OFDM: Theory and design," Opt. Exp., vol. 16, pp. 842–859, Jan. 2008.

[3] A. Li1, X. Chen, G. Gao1, A. Al Amin1, W. Shieh, and B. S. Krongold, "Transmission of 1.63-Tb/s PDM-16QAM Unique-word DFT-Spread OFDM Signal over 1,010-km SSMF," Optical Society of America, Jan. 2012.

[4] W. Shieh and C. Athaudage, "Coherent Optical Orthogonal Frequency Division Multiplexing", Electron. Lett., Vol. 42, pp. 587–588, 2006.

[5] Y. Ma, Q. Yang, Y. Tang, S. Chen, and W. Shieh, "1-Tb/s per channel coherent optical OFDM transmission with subwavelength bandwidth access," Optical Society of America, 2009.

[6] R. Dischler and F. Buchali, "Transmission of 1.2 Tb/s continuous waveband PDM-OFDM-FDM signal with spectral efficiency of 3.3 bit/s/Hz over 400-km of SSMF," Optical Society of America, 2009.

[7] T. H. Lotz, X.Liu, S. Chandrasekhar, P. J. Winzer, H. Haunstein, S. Randel, "Coded PDM-OFDM Transmission With Shaped 256-Iterative-Polar-Modulation Achieving 11.15-b/s/Hz Intrachannel Spectral Efficiency and 800-km Reach", IEEE J. Lightwave Technology, Vol. 31, No. 4, Feb. 2013.

[8] R. Tripathi, R. Gangwar and N. Singh, "Reduction of Crosstalk in Wavelength Division Multiplexed Fiber Optic Communication Systems", Progress In Electromagnetics Research, PIER, 2007.

[9] S. L. Jansen, "Optical OFDM for Long-Haul Transport Networks," Nokia Siemens Networks, Germany, OFC 2008.

[10] W. Shieh and I. Djordjevic, "OFDM for Optical Communications", 1st ed. Academic Press, UK: Elsevier Inc., 2010.

[11] S. Kumar (Ed.), "Impact of Nonlinearities on Fiber Optic Communications", Chapter 2, "Optical OFDM Basics", Q. Yang, A. Al Amin, and W. Shieh, 1st ed. Springer Inc., 2011.

[12] J. Armstrong, "OFDM for Optical Communications", Journal of Lightwave Technology, Vol. 27, No. 3, February, 2009.

[13] "OptiSystem, Component Library", Optiwave corp., 2012.

[14] W. Shieh, H. Bao, and Y. Tang, "Coherent Optical OFDM: Theory and Design", Optics Express, vol. 16, pp. 841–859, 2008.

[15] W. Shieh, R. S. Tucker, W.Chen, X.Yi, and G. Pendock, "Optical Performance Monitoring in Coherent Optical OFDM Systems", Optical Society of America, Vol. 15, No. 2, Optics Express 350, January, 2007.

[16] M. Mayrock and H. Haunstein, "Spectral Efficiency Limitation by Fiber Non-linearity in Optical OFDM Transmission Systems", Provided by Alcatel-Lucent, University Erlangen-Nurnberg, Germany, 2009.

[17] S. L. Jansen, I. Morita, T.C.W. Schenk, D. van den Borne and H. Tanaka, "Optical OFDM - A Candidate for Future Long-Haul Optical Transmission Systems", Optical Society of America, 2007.

[18] W. Shieh, X. Yi, and Y. Tang, "Transmission experiment of multigigabit coherent optical OFDM systems over 1000km SSMF fiber," Electronics Letters, Vol. 43, No. 3, pp. 183–184, 2007.

[19] A. J. Lowery, L. Du, and J. Armstrong, "Orthogonal frequency division multiplexing for adaptive dispersion compensation in long haul WDM systems," in Proc. and the 2006 National Fiber Optic Engineers Conf. Optical Fiber Communication Conf. OFC 2006, pp. 1–3, 2006.