



Effect of Fiber Nonlinearity on the Performance of WDM Dual-Polarization Coherent Optical OFDM Systems

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ABSTRACT

In recent years, there is increasing interest in using dual-polarization (DP) technique to enable future systems with at least 100 Gb/s rate per channel to operate over existing optical networks. The performance of these advanced systems can be enhanced further by using coherent optical orthogonal multiplexing (CO-OFDM) technique which offers high spectral efficiency and outstanding tolerance of fiber dispersion. This paper addresses the effect of fiber nonlinear optics on the performance of dual-polarization wavelength-division multiplexing (WDM) CO-OFDM systems operating with 100 Gb/s per channel. Different modulation formats, namely BPSK, QPSK and 16-QAM, are used. First, the performance of a single-channel system is investigated in the absence and presence of fiber nonlinearity. The results are compared with a conventional (single-polarization) system to identify the key role played by the DP technique. The investigation is then extended to WDM systems incorporating DP-OFDM technique. The results reveal that the effect of fiber nonlinearity can be reduced by using optimum transmitter laser power P_{opt} . Further, the value of P_{opt} is a function of transmission distance, number of multiplexed channels, and modulation formats. P_{opt} of -11, -12, and -5 dBm is needed for a ten-channel DP system operating with BPSK, QPSK, and 16-QAM formats, respectively. Simulation results presented in this work are obtained using *Opti System* (version 11.1) which is a commercial software package.

Indexing terms/Keywords

Optical Orthogonal Frequency Division Multiplexing (OOFDM); Dual-Polarization OFDM (DP-OFDM); Coherent OFDM (CO-OFDM); Wavelength-Division Multiplexing OFDM (WDM-OFDM); Fiber Nonlinear Optics.

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1. INTRODUCTION

Fiber optics underpins the communication infrastructure of today's information society. Rapid progress in advanced modulation formats, high-gain coding, optical amplification, coherent detection with digital signal processing, and new types of transmission fibers have significantly affected optical communications [1]. The capacity of a single-channel optical communication system operating under ideal conditions (i.e., perfect compensation of fiber attenuation and dispersion) is generally limited by the speed of electronics used in the transmitter and receiver sides which is up to 50 Gb/s [2,3].

Different techniques have been adopted in the literature to enhance the capacity of optical communication systems such as

- (i) **Wavelength-division multiplexing (WDM)** where several channels of high speed data, each with a unique wavelength, can be packed into a single fiber [4,5]. By the early 2000s, the rapid advances in optical, electronic and optoelectronic device technologies allow for 50 GHz WDM channel spacing, and electronically generated and directly detected 40 Gb/s per channel binary optical signals. Then research had started to investigate WDM systems employing direct detection/differential binary and quaternary phase shift keying (DPSK, DQPSK) leading to commercial deployment at 40 Gb/s [6, 7].
- (ii) **High-order modulation formats** to increase the spectral efficiency [5, 6]. Moving from binary format to M-ary format will enhance the spectral efficiency from 1 b/Hz to $(\log_2 M)$ b/Hz. The features and limitation of high-order signaling format was discussed by Winzer [8] and can be summarized as follow. The best optical modulation format is frequently encountered in optical transmission system design and depends on system requirements. Among these requirements are target per-channel interface rate, available per-channel optical bandwidth, target WDM capacity (or spectral efficiency), target transmission reach, optical networking requirements, and transponder integration and power consumption. To generate a square-QAM constellation using a single inphase / quadrature (I/Q) modulator (driven by two quadrature signals with amplitude levels), one needs two digital-to-analog converters (DACs), each with a minimum resolution of bits, at a sampling rate equal to the symbol rate. Having higher-resolution DACs allows for compensation of modulator or driver nonlinearities; having over-sampled DACs further allows for digital pulse shaping. Commercial DACs built in CMOS technology are currently available up to 65 Gsamples/s with as much as 8-bit resolution, capable of producing constellations beyond 16-QAM.
- (iii) **Optical orthogonal frequency-division multiplexing (OFDM)** where a large number of parallel narrow-band subcarriers instead of a single wide-band carrier are used to transport information [9, 10]. The OFDM technique offers high spectral efficiency and outstanding tolerance of chromatic dispersion and polarization-mode dispersion. There are different architectures for optical OFDM which can be classified into two main categories, direct-detection optical OFDM (DDO-OFDM) [11] and coherent optical OFDM (CO-OFDM) [12]. Direct-detection transmission uses a very simple receiver that usually only requires photodiodes for detection but has limited transmission performance that might restrict its application only to short-reach networks. In contrast, coherent detection is emerging as the most attractive candidate for next-generation fiber communication systems. A coherent detector is highly sensitive and can detect all the information about the optical field, including amplitude, phase, and polarization. This enables linear and nonlinear fiber impairments to be compensated by using digital signal processing (DSP) [13].
- (iv) **Hybrid technique** which incorporates OFDM in WDM systems. Recently, channel capacity exceeding 1 Tb/s has been demonstrated by different research groups in OFDM-WDM networks [14].

In recent years, there is increasing interest in using dual-polarization (DP) technique to enable future systems (at least at 100 Gb/s) to operate over existing optical networks with 50 GHz WDM channel spacing. Each channel uses polarization-division multiplexing (PDM) where the data is split in two parts and each part is used to modulate one of the two orthogonally polarized components of the carrier [15,16]. Figure 1 shows the advanced modulation formats to be used in ultra-high-capacity WDM transmission system for 100 Gb/s and beyond per channel which stand heavily on PDM [17].

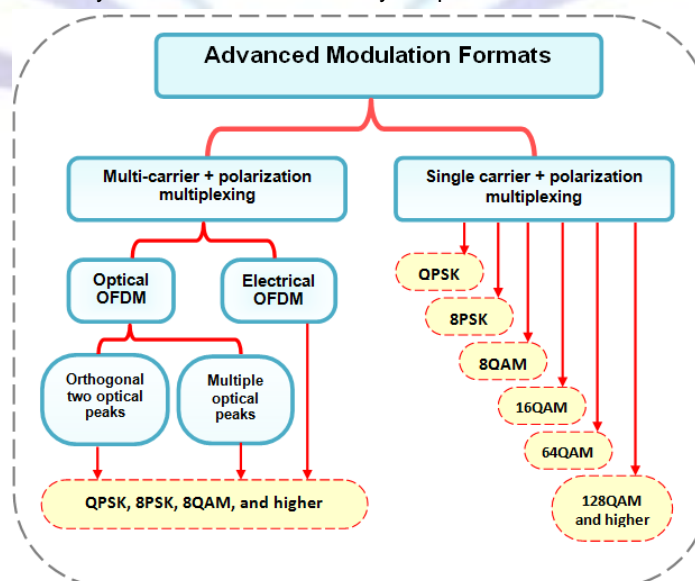


Fig. 1: Advanced modulation formats for ultra-high-speed single channel operating at 100 Gb/s and beyond [17].



The dual-polarization CO-OFDM has also been introduced in WDM systems to enhance the capacity against the conventional (single-polarization) counterpart [18]. However, the performance of these advanced system is still affected (as other WDM systems) by fiber dispersion and nonlinear fiber optics. Chromatic dispersion is usually a dominant factor that distorts the optical waveform as it propagates along the fiber. In most fiber links, chromatic dispersion is optically compensated for by cascading two or more kinds of fiber with inverse dispersion parameters. New inverse dispersion fibers compensate for both dispersion and dispersion slope while minimizing the total polarization mode dispersion (PMD). This results in wideband dispersion flatness [13]. With coherent detection, chromatic dispersion and PMD can also be compensated by using DSP. Fiber nonlinearity imposes a major impairment that limits the achievable transmission distance and channel capacity. Nonlinear impairments, including self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) increase with the power launched into the fiber. As linear impairment compensation technology matures, nonlinear effects become the factor that limits the capacity and transmission distance of long-haul fiber communication systems [13]. Therefore, it is essential to investigate the effect of fiber nonlinearities on the performance of WDM system incorporating dual-polarization CO-OFDM. This issue is addressed in this work.

2. RELATED WORK

In 2013, Horlin et al. [19] proposed a receiver architecture that could decouple the two polarizations in DP-OFDM with offset QAM (OFDM-OQAM) system. An equalizer per channel was built at twice the symbol rate and optimized using minimum mean square error (MMSE) criterion. The efficiency of the resulting system was compared to the Nyquist WDM (N-WDM) system both in terms of performance and complexity. The results reveal that using the OFDM-OQAM modulation combined with PDM in coherent optical fiber communications will lead to double the spectral efficiency. More specifically, the MMSE equalizer working per channel at twice the symbol rate was designed to decouple the two polarization signals, and its efficiency was assessed numerically. Compared to the well studied N-WDM system, the proposed system benefits from an improved BER performance when the pulse shaping filters are of identical length, or equivalently from a reduced computational complexity to achieve an identical BER. The results reveal that the synchronization requirements of time and phase were actually not stringent.

In 2013, Karaki et al. [20] experimentally compared the transmission performance of coherent dual-polarization multi-band (DP-MB) OFDM and QPSK (DP-QPSK) for 100 Gb/s long-haul transport over legacy infrastructure combining G.652 fiber and 10 Gb/s WDM system. It was shown that DP-MB-OFDM and DP-QPSK have nearly the same performance at 100 Gb/s after transmission over a 10 x 100-km fiber line. Furthermore, they explored numerically that an error free transmission over 1200 km is feasible for the 100 Gb/s DP-MB-OFDM system. It was also verified that DP-MB-OFDM is sensitive to the nonlinear inter-band crosstalk effects induced by FWM. The validity of the numerical model was verified with the experimental measurements.

3. OPTICAL ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

Orthogonal frequency division multiplexing is a modulation technique which is now used in most new and emerging broadband wired and wireless communication systems. The fundamental principle of OFDM was proposed as a way to overlap multiple channel spectra within limited bandwidth without interference. Hence this technique can squeeze multiple modulated subcarriers tightly together at a reduced bandwidth without the requirement for guard bands while at the same time keeping the modulated signals orthogonal so that they do not interfere with each other [21].

In recent years, there have been intensive studies on optical OFDM (O-OFDM) transmission technologies, and it is considered a promising technology for future ultra-high-speed optical transmission [22]. The O-OFDM is an effective solution to compensate the linear distortions, such as group-velocity dispersion (GVD) and PMD [23, 24]. Based on OFDM technology, novel elastic optical network architecture with immense flexibility and scalability in spectrum allocation and data rate accommodation could be built to support diverse services and the rapid growth of Internet traffic in the future [25].

Optical OFDM technology has a number of advantages that are key to future transmission systems [26]

- OFDM transmits a high-speed data stream by dividing it into multiple low-data-rate subcarriers, thereby increasing the symbol duration and reducing the intersymbol interference (ISI). The intrinsic resilience to ISI makes O-OFDM a good candidate for future high-speed communication systems.
- O-OFDM enables smooth upgrading from low-speed to high-speed transmission by simply augmenting the subcarriers and spectrum, without major changes in system design. Therefore, it is highly scalable for migration to the ever-increasing data rate in the future.
- High spectrum efficiency can be achieved by O-OFDM with overlapped subcarrier arrangement, so the system capacity can be greatly increased.
- The link-adaption capability of O-OFDM provides even higher spectrum efficiency, as distance and channel condition-adaptive modulation (bit per symbol adjustment) is employed.
- Energy-efficient operation to reduce power consumption can be implemented by an O-OFDM system through adaptive modulation and dynamically switching on/off specific subcarriers according to the channel condition and customer bandwidth requirement.

For applications within optical fiber communications it is necessary to incorporate an optical source to convert the electrical OFDM signals into an optical signal format before coupling onto an optical fiber. At the receiving end, the intensity modulated signal can be recovered using either direct detection or coherent detection. DDO-OFDM is realized by sending the optical carrier along with the OFDM baseband so that direct detection with a single photodiode can be used at the receiver to convert the optical field back into the electrical domain [27] (see Fig. 2). The advantage of this technology is

its relatively-simple implementation and low cost. Therefore, DDO-OFDM has a broader range of applications, such as long-haul transmission. However, DDO-OFDM is less bandwidth efficient, and it has lower performance in receiver sensitivity compared to CO-OFDM [28].

Coherent O-OFDM uses local laser source to achieve coherent demodulation which offers high selectivity and sensitivity but yet requires the highest complexity in transceiver design [29].

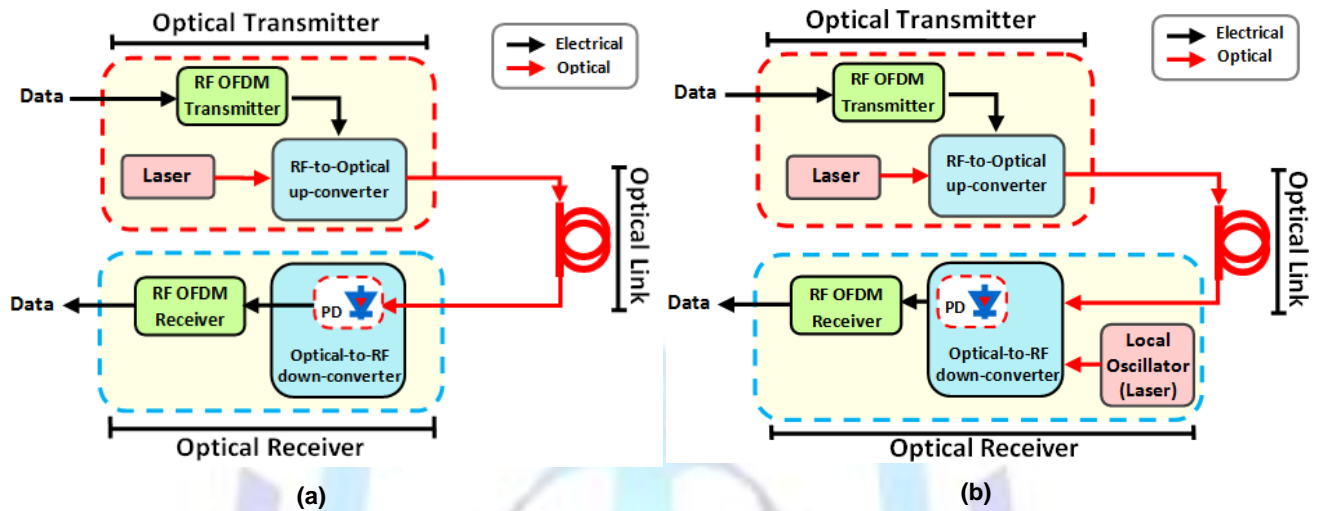


Fig. 2: Schematic diagrams of optical OFDM system. (a) Direct-detection architecture. (b) Coherent detection architecture.

The dual polarization O-OFDM consists mainly from two single-polarization counterparts, one for each polarization. The output of the transmitter laser is split into two orthogonal polarizations. Each polarization component is modulated by one of the data stream as illustrated in Fig. 3.

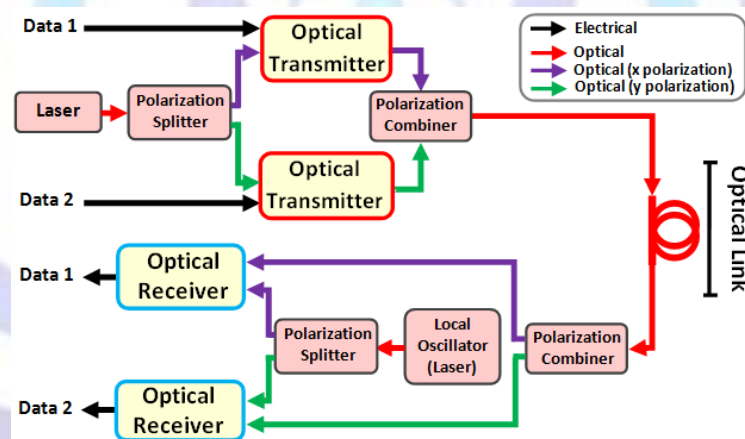


Fig. 3: Schematic diagram of dual polarization CO-OFDM.

4. PERFORMANCE OF SINGLE-CHANNEL COHERENT OFDM SYSTEMS

The performance of optical CO-OFDM systems, like other optical communication systems, is affected by both linear and nonlinear impairment of the optical fiber. Optical amplifiers and DCFs can be inserted in the transmission link to compensate fiber losses and chromatic dispersion, respectively. This leaves the fiber nonlinearity playing a key role in determining system performance. The aim of this chapter is to investigate the effect of fiber dispersion and nonlinear optics on the performance of single-channel CO-OFDM systems. For purpose of comparison, three systems are investigated here, namely 100 Gb/s dual polarization (DP), 50 Gb/s single polarization (SP), and 100 Gb/s SP. The simulation results presented in this section will be used as a guideline to investigate the performance of WDM systems in next section.

4.1 System Configuration

The single-channel CO-OFDM system is used to investigate the nonlinearity effect on the optical link. The detailed configuration of the system is given in Table 1 to summarize the components description and parameters values for the main five parts of the CO-OFDM transmission link.



Table1: Components description and parameters values used in the simulation.

Parameter	Value	Unit	Parameter	Value	Unit	Parameter	Value	Unit
A. Transmitter			B. Optical Channel			C. Receiver		
i. Transmitter Laser			i. Single mode fiber (SMF)			i. Local oscillator (LO) laser		
Frequency	193.1	THz	Length	80	km	Frequency	193.1	THz
Power	-4	dBm	Attenuation	0.2	dB/km	Power	-4	dBm
Line width	0.15	MHz	Group Velocity Dispersion	16	ps/nm-km	Linewidth	0.15	MHz
Initial phase	0	deg.	PMD	0.3	ps/km	Initial phase	0	deg.
Polarization (Azimuth)	45	deg.	Dispersion Slop	0.075	ps/km-nm ²	Polarization (Azimuth)	45	deg.
Polarization (Ellipticity)	0	deg.	Effective area	80	μm ²	Polarization (Ellipticity)	0	deg.
ii. Polarization Splitter			n2	2.6x10 ⁻²⁰	m ² /W	ii. Polarization Splitter		
Device angle	0	deg.	ii. Optical Amplifier for SMF			Device angle	0	deg.
iii. Modulation Format			Gain	16	dB	iii. X-Coupler		
BPSK			Noise figure	4	dB	Coupling coefficient	0.5	
QPSK			iii. Dispersion compensation fiber (DCF)			Additional loss	1	dB
16-QAM			Length	16	km	iv. Phase shift		
iv. Electrical OFDM generator			Attenuation	0.5	dB/km	Device shift	90	deg.
Number of subcarriers	512		Group Velocity Dispersion	-80	ps/nm-km	v. Photo detector (PD)		
Position array	256		Effective area	22	μm ²	Responsivity	1	A/W
Number of FFT points	1024		n2	2.6 x 10 ⁻²⁰	m ² /W	Thermal noise	100 x 10 ⁻²⁴	W/Hz
v. X-Coupler			iv. Optical Amplifier for DCF			vi. Electrical OFDM Recover		
Coupling coefficient	0.5		Gain	8.002945	dB	Number of subcarriers	512	
Additional loss	1	dB				Position array	256	
vi. Mach-Zehnder Modulator (MZM)						Number of FFT points	1024	
Extinction ratio	60	dB				vii. Bit-error-rate (BER) Analyzer		
Switching bias voltage	4	V				Algorithm	Gaussian	
Insertion loss	1	dB				Decision instant	0.5	Bit period
vii. Polarization Combiner						Lower/Upper calculation limit	0/1	Bit period
Device angle	0	deg.						
viii. Optical Amplifier-Booster								
Gain	13	dB						
Noise figure	4	dB						

RF OFDM transmitter, the OFDM signal is synthesized in the electrical domain with different modulation formats that achieve high spectral efficiency within limited bandwidth. Table 2 shows summary of the modulation formats used in the simulation for 50 Gb/s data rate B.

Table2: Modulation formats used in the simulation.

Modulation Format	BPSK	QPSK	16-QAM
Power (w)			
Bandwidth (BW)	B	B/2	B/4
Bit per Hz	1	2	4

At the RTO up-converter, a transmitter laser output power is split into two parts (I and Q carriers) using X-coupler, where the two parts are fed into I/Q modulator to up-convert the RF signal to the optical domain yielding an O-OFDM signaling as shown in Fig. 4. The I/Q modulator has two MZMs that serve I or Q component. Each MZM divides the incoming laser field into two arms (positive and negative) signals, which are subsequently recombined at the optical output of the MZM. The I and Q components of the RF OFDM controls the intensity of the output optical signal by controlling the degree of interference at the MZM output. The output signals from the two MZMs are combined by using an optical combiner to produce O-OFDM signal that transmitted in the optical channel. The signal propagates through a SMF and becomes degraded due to fiber impairments while it is propagating through the transmission link.

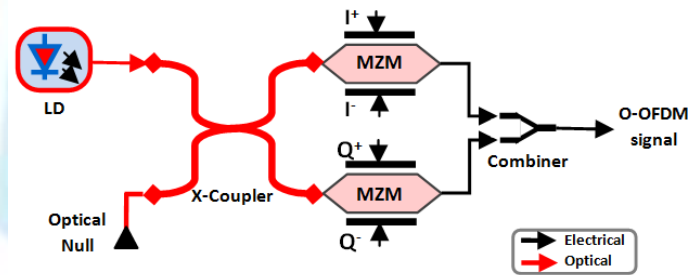


Fig. 4: Detailed configuration of the optical OFDM.

At the receiver side, the OTR down-converter and the local oscillator (laser) are used to down-convert the signal to the RF domain by using four X-couplers, phase shifter, four PIN photodetectors and two electric substractors (see Fig. 5).

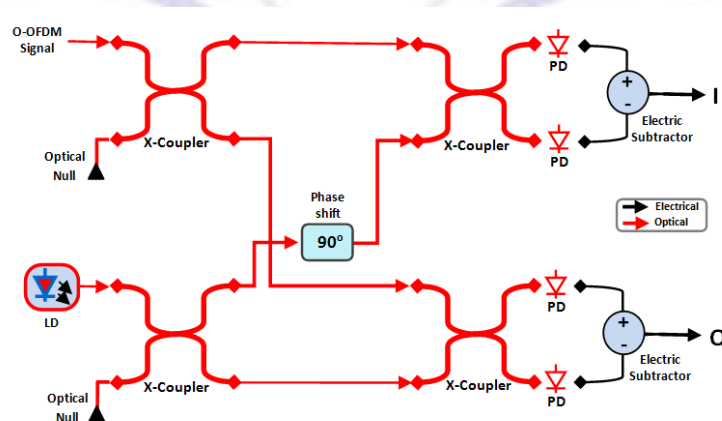


Fig. 5: Detailed description of the OTR conversion in the receiver.

4.2 Single-Polarization System

This section addresses the effect of dispersion and optical fiber nonlinearity on the performance of single-polarization CO-OFDM system operating at 50 Gb/s data rate.

4.2.1 Dispersion and Losses in the Optical Link

In optical communications, the linear degradation of the optical signal usually affects the performance of the system. In order to show the effect of the linear degradation (attenuation, chromatic dispersion, and PMD) on the system performance, two points are to be considered in the absence of nonlinearity fiber optics. Firstly, the results corresponding to the constellation diagrams and BER values of the received signal should be monitored. Secondly, the system performance should be checked in back-to-back (B2B) configuration (i.e., no fiber link) to ensure zero BER, and then the 80 km SMF is inserted.

The linear degradation of the system can be divided into two major problems. The first one can be solved using optical amplifier to compensate the attenuation via the fiber. The second is solved by using DCF to eliminate the effect of the dispersion in the fiber.

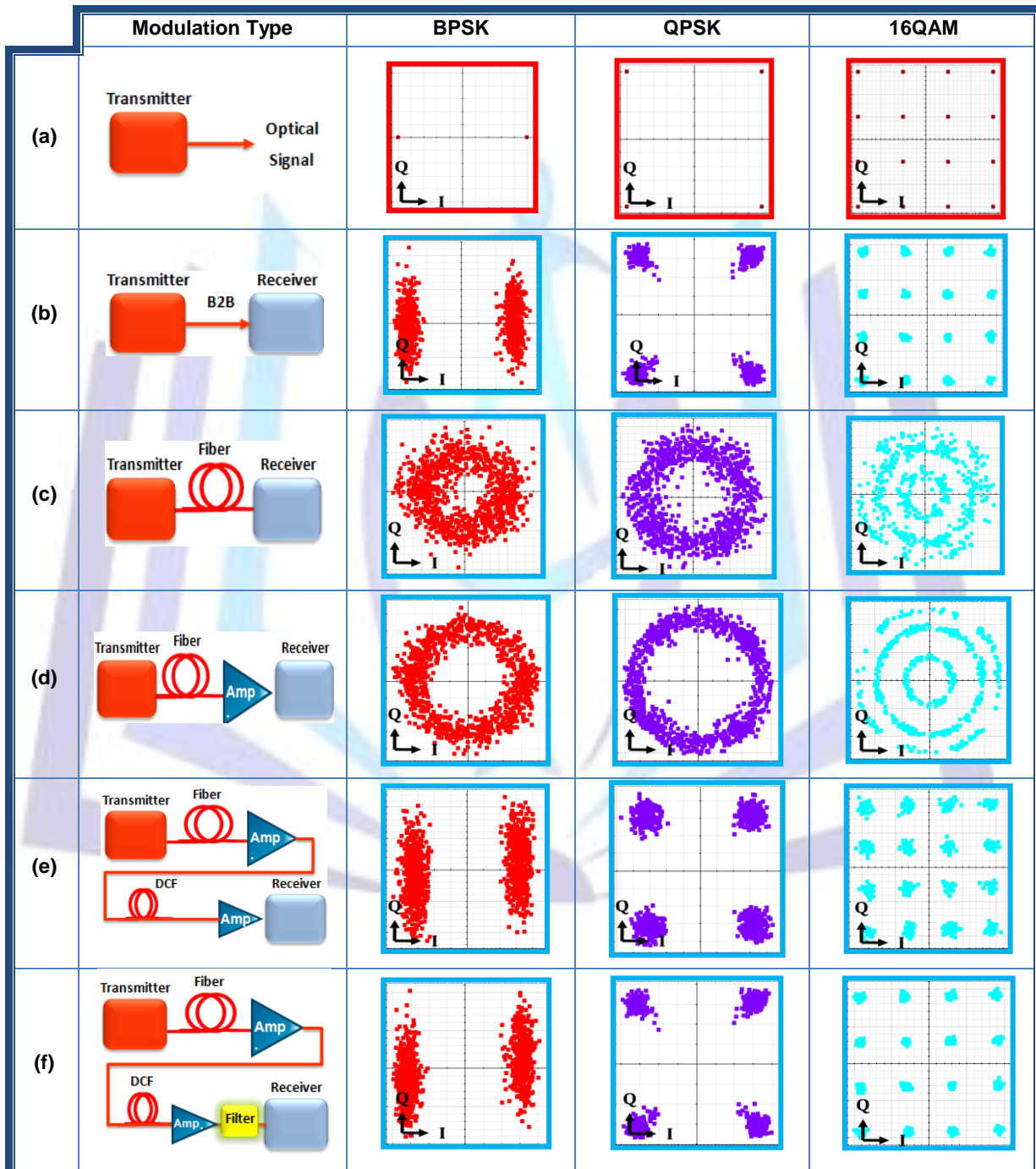


Fig. 6: Performance of a single-polarization system for different span configuration. (a) Transmitted signal of Back-to-Back configuration (direct connection between the transmitter and the receiver). (b) Received signal of Back-to-Back configuration (c) The span consists of 80 km SMF only. (d) The span consisting of 80 km SMF and 16 dB optical amplifier. (e) The span consisting of 80 km SMF, 16 dB optical amplifier, 16 km DCF, and 8 dB optical amplifier. (f) Optical filter after the span (80 km SMF, 16 dB optical amplifier, 16 km DCF, and 8 dB optical amplifier).

Figure 6 shows the effect of the chromatic dispersion and PMD on system performance and Table 3 lists the corresponding BER. The starting point is the system without using the dispersion compensation (that means chromatic dispersion and PMD affect the system performance) and then the DCF is used to improve the quality of the received signal at the end of the optical channel. Finally, optical filter is used at the end of the transmission link to suppress partially the amplified spontaneous emission (ASE) noise introduced by the optical amplifier.

Table3: BER corresponding to each type of span.

Span Type	Span Description	BER		
		BPSK	QPSK	16-QAM
a	Back-to-Back	0	0	0
b	80 km SMF	0.43168093	0.38563746	0.32326392
c	80 km SMF + 16 dB Amplifier	0.43031994	0.37868593	0.17963811
d	80 km SMF + 16 dB Amplifier + 16 km DCF + 8 dB amplifier	0	0	0
e	80 km SMF + 16 dB Amplifier + 16 km DCF + 8 dB amplifier + filter	0	0	0

Investigating the results in Fig. 6 highlights the following findings

- (i) The system is working properly without any error for a single span link.
- (ii) In parts (d) and (e), the two cases may seem alike, but they have different performance at long distances since the optical filter reduces the effect of ASE associated with the signal. For example, operating the system with the optical filter gives a BER of 3.2×10^{-9} , 9.4×10^{-8} , and 1×10^{-6} for BPSK, QPSK, and 16-QAM modulation formats with 29, 24, and 9 spans, respectively. The system without filter gives 1.4×10^{-3} , 2.8×10^{-2} , and 2.1×10^{-2} , respectively.
- (iii) To achieve the best BER along the transmission link, the span described in part (e) is used for the rest of simulations described in the rest of this chapter and chapter four.

Figure 7 shows the power spectral density of the transmitted and received optical OFDM signal for different modulation formats corresponding to a transmission distance of one span.

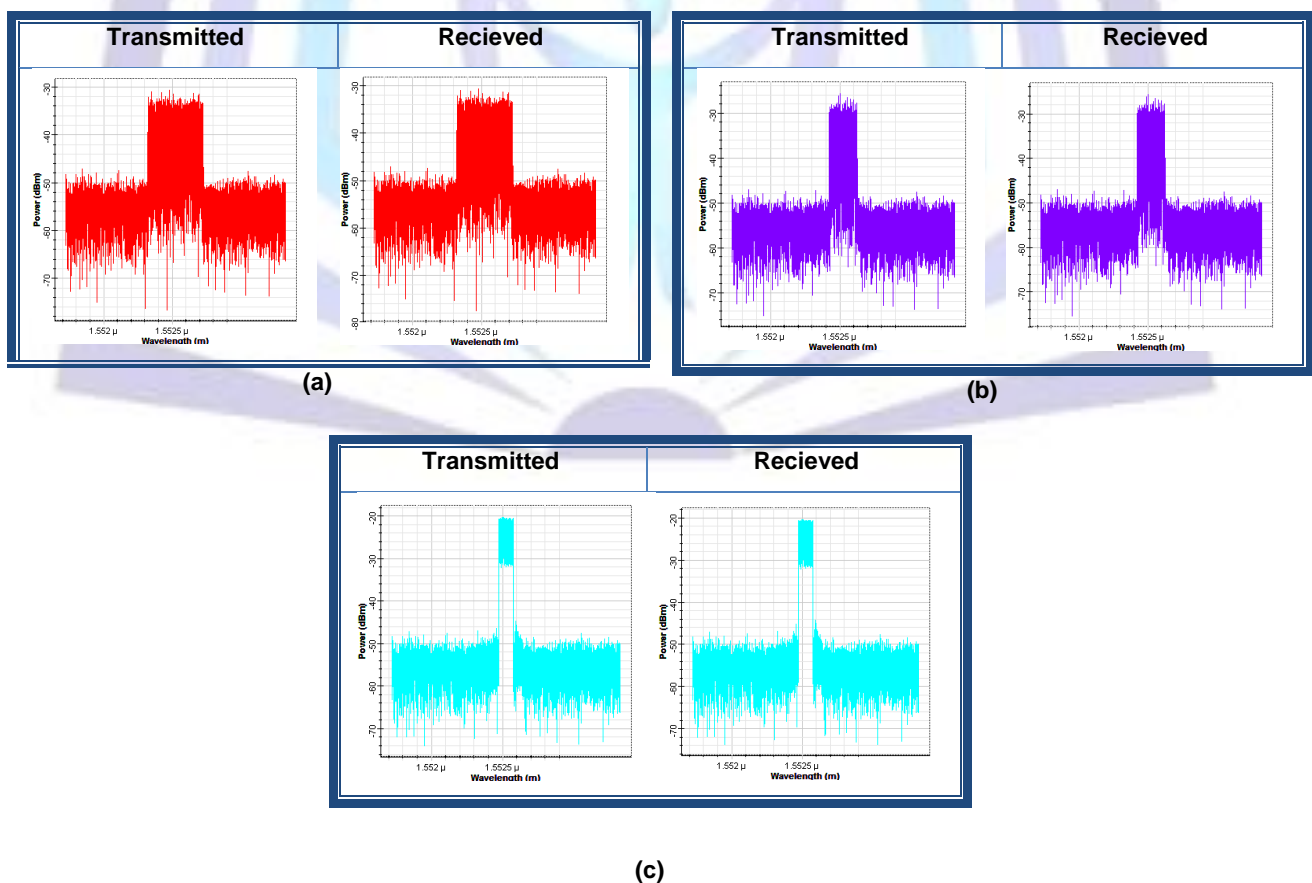


Fig. 7: Power spectral density of the transmitted and received optical OFDM signal over a single-span link. (a) BPSK. (b) QPSK. (c) 16-QAM.

4.2.2 Nonlinearity Effect

It is clear that, the influence of linear degradation imposed by the optical fiber can be compensating as shows in Section 4.2.1. Meanwhile the nonlinearity effect plays a very important role to limit transmission signal over long-haul distances of optical communication systems. This issue is addressed here for single-polarization CO-OFDM system.

Figure 8 shows how the nonlinearity affects the system performance for different modulation formats (BPSK, QPSK and 16-QAM). The calculation is performed after inserting an optical amplifier to compensate the span losses and DCF to compensate the span chromatic dispersion. The figure contains two parts corresponding to the absence and presence of nonlinearity. Note that to achieve a BER less than 10^{-9} , the number of spans should be less than 325, 275, and 115 for BPSK, QPSK, and 16-QAM formats, respectively, in the absence of fiber nonlinearity. The presence of nonlinear fiber optics reduces the maximum allowable number of spans to 29, 23, and 8, respectively. Figure 9 illustrates the received constellation diagrams for different modulation formats to highlight the effect of the nonlinearity of the fiber.

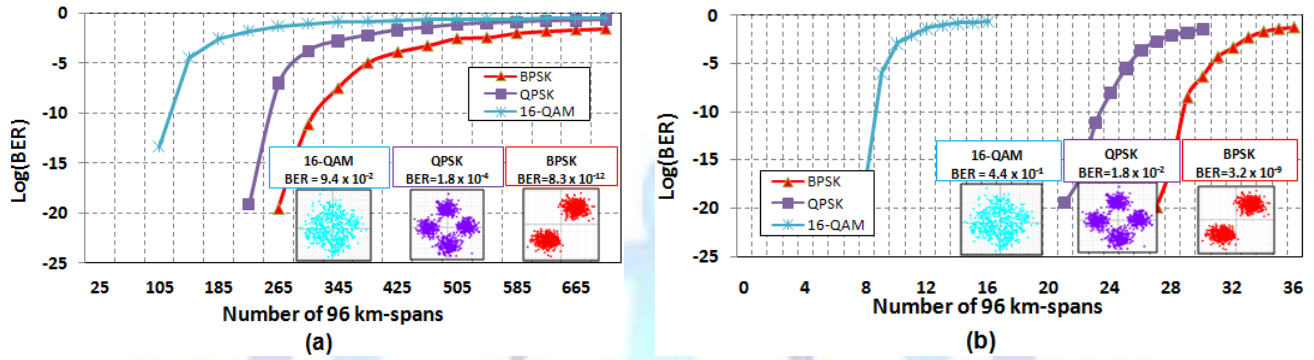


Fig. 8: BER versus number of spans for 50Gb/s single polarization. (a) Without nonlinearity effect (The insert shows the constellation diagrams after 305 spans). (b) With nonlinearity effect (The insert shows the constellation diagrams after 29 spans).

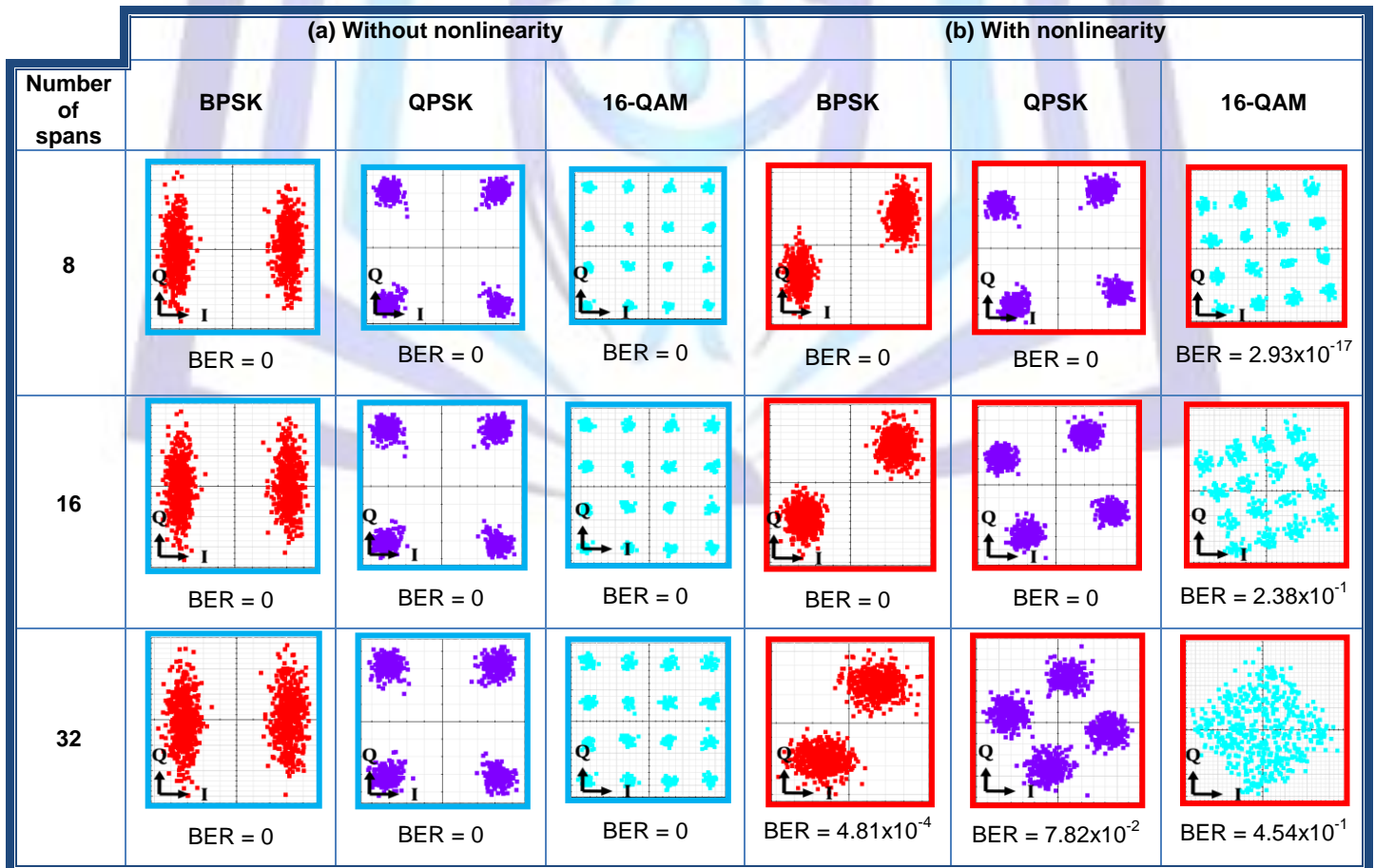


Fig. 9: Received constellation diagrams of 50 Gb/s single polarization for three different modulation formats (BPSK, QPSK, and 16-QAM). (a) Without nonlinearity effect. (b) With nonlinearity effect.

4.2.3 OFDM Effect

Despite the impact of fiber degradation on the CO-OFDM signal, but this effect becomes stronger when one removes the presence of OFDM technique. As explained previously, the OFDM technique is part of the solution to the problem that causing the quality decay of the optical signal during passage in the optical channel of the system.

Figure 10 illustrates the variation with number of spans for conventional QPSK optical communication system (i.e., without OFDM technique). The results are compared with the QPSK-OFDM system. A 96 km-span is used consisting of 80 km-SMF, 16 km-DCF, and two optical amplifiers (16 and 8 dB). As shown in the figure, the optical signal with OFDM technique has the ability to reach farther distances compared with the other system with the same BER. For example, at $BER = 10^{-9}$, the maximum allowable number of spans is 16 and 23 in the absence and presence of OFDM, respectively.

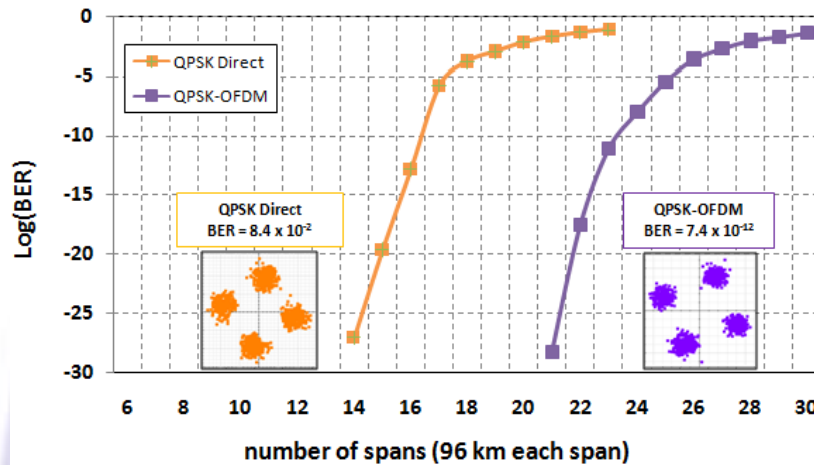


Fig. 10: Nonlinearity effect on the performance QPSK-OFDM and conventional QPSK optical communication systems (The insert shows the constellation diagrams after 23 spans).

4.3 Dual-Polarization System

In order to optimally exploit the bandwidth and to achieve more information data that can be transmitted over long-haul distance bandwidth doubling using a dual-polarization technique can be adopted. This is especially compatible with 50GHz channel spacing according to ITU G.694.1 that is used in the WDM system as will shown later. However, a debate exists over the DP transmission technologies to be as efficient to increase the capacity of the optical network, but it suffers from the fiber nonlinearities effect.

For the DP optical OFDM system considered here, a transmitter laser is used with polarization angle (azimuth) of 45° . The polarization splitter divides the laser field into two equal parts, each part is modulated via an electrical CO-OFDM signal. The two modulated optical waves are then combined using a polarization combiner. At the receiver side, two polarization splitters are used to split the orthogonal polarization components of the received optical signal and the local oscillator (laser) field. The incident angle (azimuth) of the local laser is set to 45° in order to recover the signal by using two CO-OFDM receiver systems (see Fig. 3).

Figure 11 shows performance comparison among three systems in the absence of nonlinear fiber optics

- System I: 100 Gb/s DP (i.e., 50 Gb/s on the x-polarization and 50 Gb/s on the y-polarization).
- System II: 50 Gb/s single polarization.
- System III: 100 Gb/s single polarization.

The simulation is carried further in Fig. 12 to include the effect of nonlinearity. Again the losses and chromatic dispersion of each span is fully compensated using optical amplifier and DCF.

Table 4 lists the maximum allowable number of spans to achieve a BER less than 10^{-9} for different modulation formats which is deduced from Figs. 11 and 12.



Table4: Comparison performance among three CO-OFDM single-channel systems (96 km for each span).

System	Modulation Format	Maximum number of spans for BER < 10 ⁻⁹	
		Absence of fiber nonlinear optics	Presence of fiber nonlinear optics
System I (100 Gb/s DP)	BPSK	305	18
	QPSK	265	14
	16-QAM	115	6
System II (50 Gb/s SP)	BPSK	325	29
	QPSK	275	23
	16-QAM	115	8
System III (100 Gb/s SP)	BPSK	175	26
	QPSK	125	22
	16-QAM	75	8

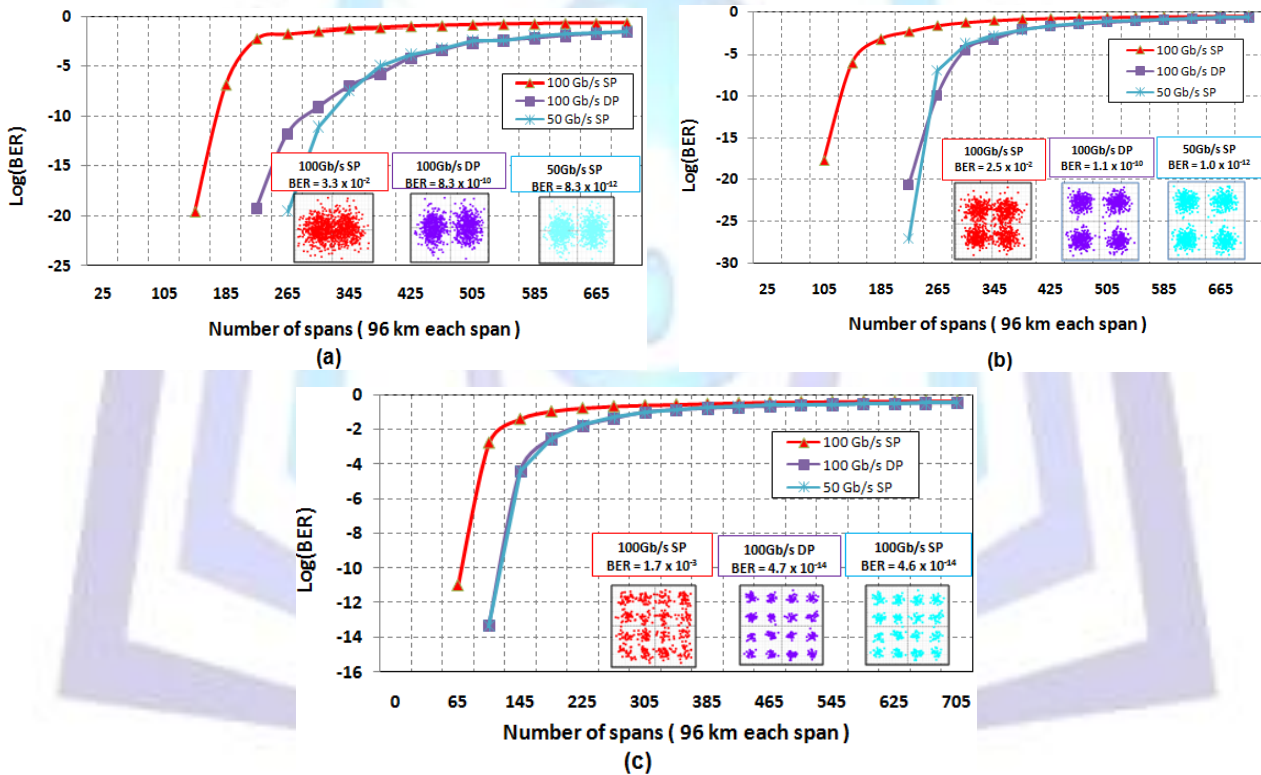


Fig. 11: BER versus number of spans for three CO-OFDM single-channel systems in the absence of fiber nonlinear optics. (a) BPSK. (b) QPSK. (c) 16-QAM (The insert shows the constellation diagrams after 305, 265, and 105 spans for BPSK, QPSK, and 16-QAM, respectively).

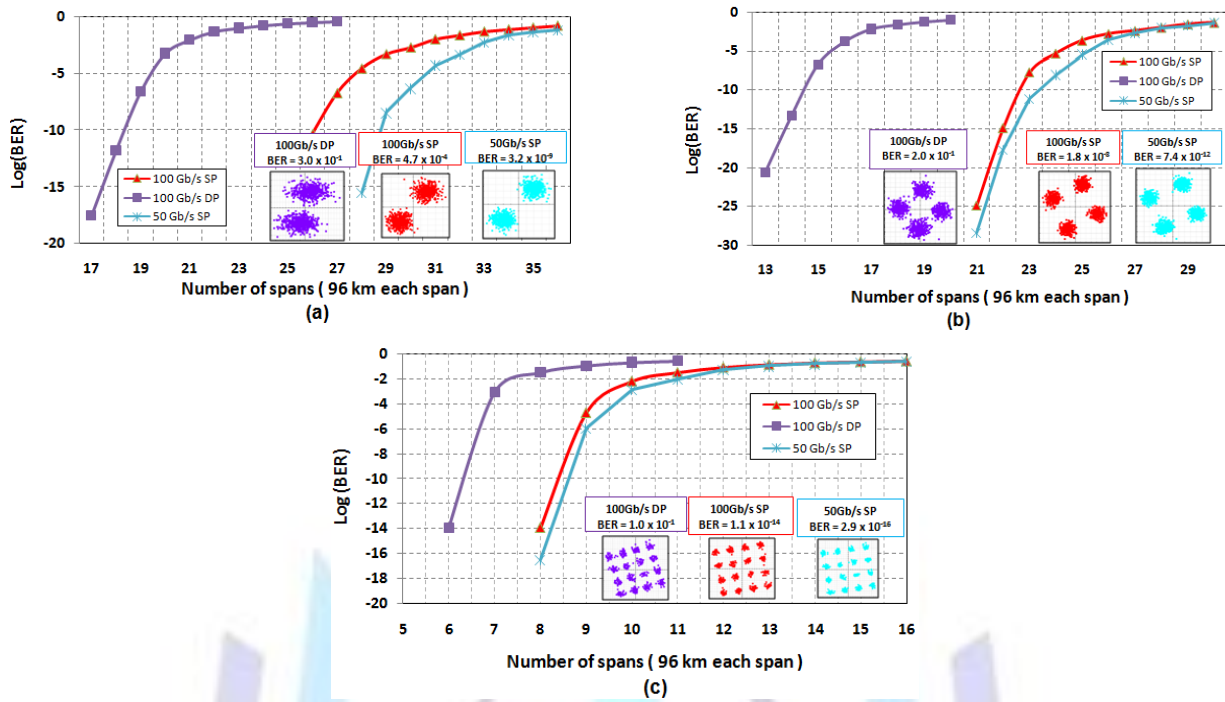


Fig. 12: BER versus number of spans for three CO-OFDM single-channel systems in the presence of fiber nonlinear optics. (a) BPSK. (b) QPSK. (c) 16-QAM (The insert shows the constellation diagrams after 29, 23, and 8 spans for BPSK, QPSK, and 16-QAM, respectively).

5. PERFORMANCE OF DUAL-POLARIZATION OFDM-BASED WDM SYSTEM

The effect of fiber nonlinear optics becomes more pronounced in WDM systems since the total power coupled to the fiber scales with number of multiplexed channels. The chapter focuses on the effect of fiber nonlinearity in WDM system incorporating 100 Gb/s dual-polarization coherent OFDM technique. The concept of optimum transmitter laser power, which ensures maximum transmission distance with received BER less than 10^{-9} , is addressed carefully for different number of multiplexed channels and modulation formats. Simulation results are presented for multi-span transmission link; each span consists of 80 km SMF, 16 dB amplifier, 16 km DCF, and 8 dB amplifier.

5.1 System Configuration

The WDM system considered here is based on multiplexing number of single channels, each using a DP CO-OFDM subsystem (i.e., 50 Gb/s for each polarization). This is useful to increase the capacity of the optical network and make a full use of the fiber bandwidth. A 50 GHz channel spacing is used to build the WDM system according to ITU G.694.1. As shown in Fig. 13, the WDM system uses an optical wavelength multiplexer (MUX) at the transmitter to combine number of single channels (different wavelengths) together into the SMF. At the receiver, an optical wavelength demultiplexer (DEMUX) is used to split them apart.

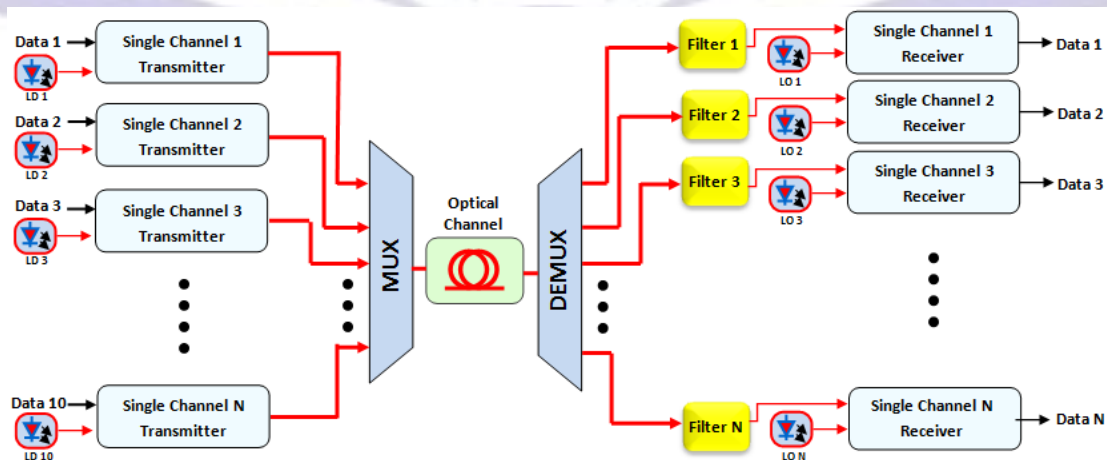


Fig. 13: WDM block diagram used in the simulation.

To investigate the influence of the nonlinear fiber optics on the WDM system, ten channels are applied in the simulation with different frequencies (different wavelengths) starting with center frequency of 193.10 THz (1552.5244 nm) with parameters values listed in Table 5. Figures 14a-c show the transmitted and received power spectra of a ten-channel WDM signal using BPSK, QPSK, and 16-QAM formats, respectively.

Table5: WDM parameters values used in the simulation.

Parameter	Value	Unit
Number of channels	10	
Starting frequency	193.1	THz
Channel spacing	50	GHz
Bit rate	50 SP	Gb/s
	100 SP	
Modulation format	BPSK	
	QPSK	
	16-QAM	
Optical filter type	Gaussian	
Filter order	2	
Multiplexer bandwidth	500	GHz

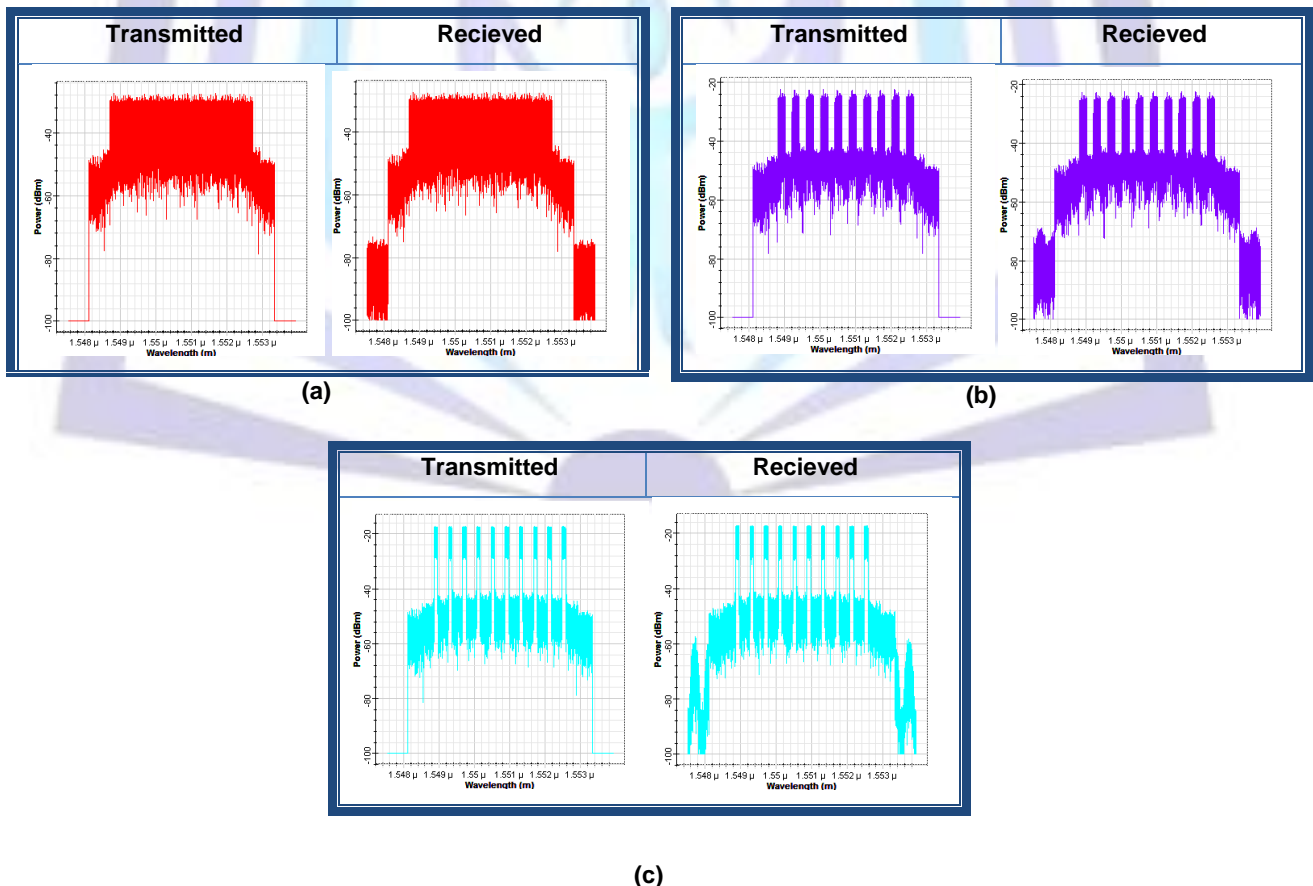


Fig. 14: Optical spectra of ten-channel WDM signal before and after the transmission over a single-span link for different modulation formats. (a) BPSK. (b) QPSK. (c) 16-QAM.

5.2 Bandwidth of the Optical Filters

An optical band-pass filter is used in front of each channel receiver to suppress partially the ASE noise introduced by optical amplification. The center frequency and bandwidth of each filter match the spectrum of the required optical signal.

Figures 15a-c show the BER as a function of the bandwidth of Gaussian optical filter used for BPSK, QPSK, and 16-QAM systems, respectively. Investigating the results in these figures reveals that the optimum filter bandwidth, which yields minimum BER, is 55, 25, and 20 GHz for the x-polarized component of BPSK, QPSK, and 16-QAM systems, respectively. These values are to be compared with 55, 25, and 20 GHz, respectively, for the y-polarized component. Note that the optimum filter bandwidth is slightly affected by type of polarization.

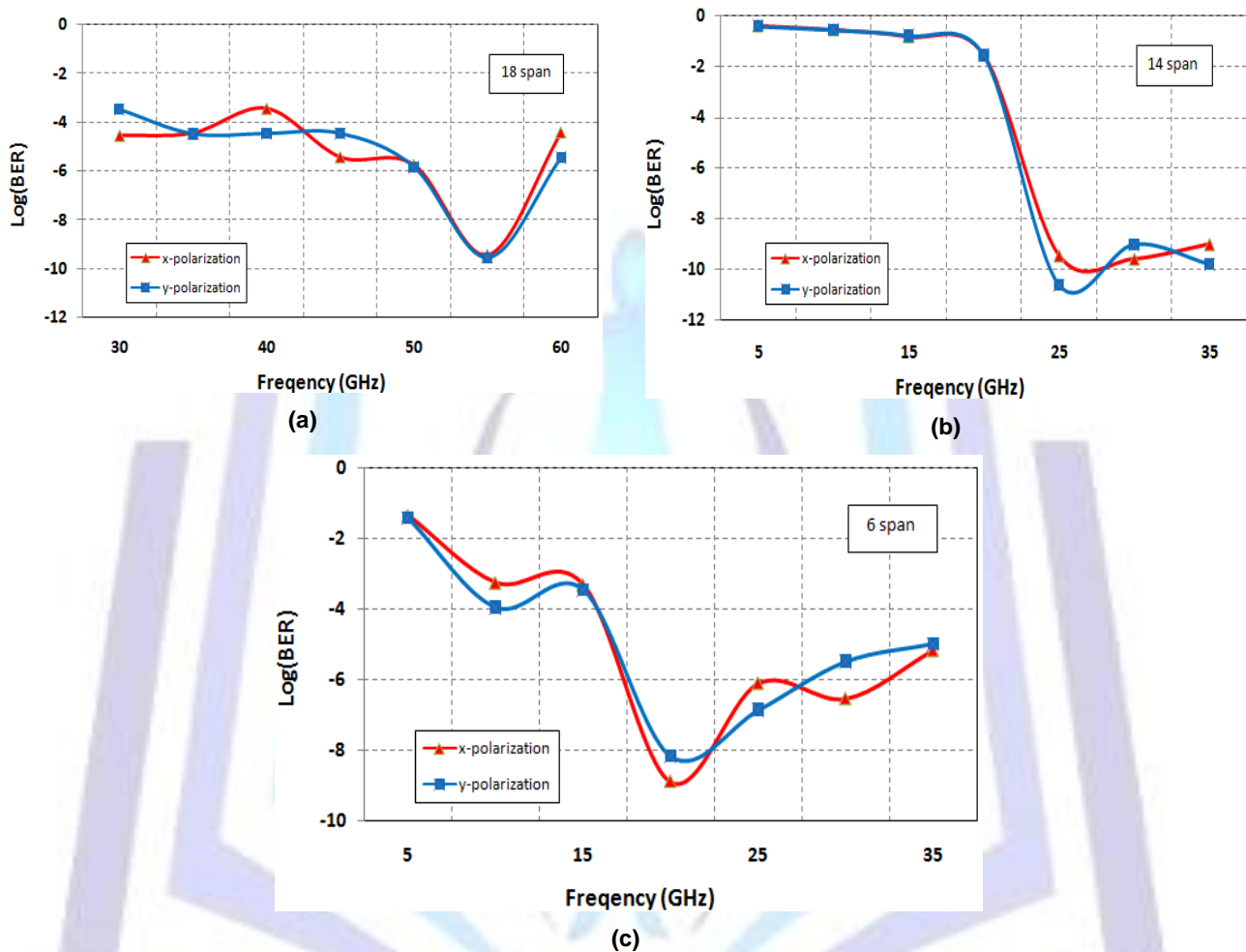


Fig. 15: BER as a function of optical filter bandwidth. (a) BPSK with 18 spans. (b) QPSK with 14 spans. (c) 16-QAM with 6 spans.

5.3 Optimum Transmitted Power

The presence of more than one optical signal inside the SMF leads to increase the impact of the nonlinearity effect due to the increase of total transmitted power. This may limit the maximum transmission distance for specific received signal quality. Figure 16 shows the effect of increasing the number of channels on the optimum transmitter laser power P_{opt} that required to transmit the optical signal with minimum BER along a fixed length for each different modulation format (BPSK, QPSK, and 16-QAM) with 29 (2784 km), 12 (1152 km), and 4 spans (384 km), respectively.

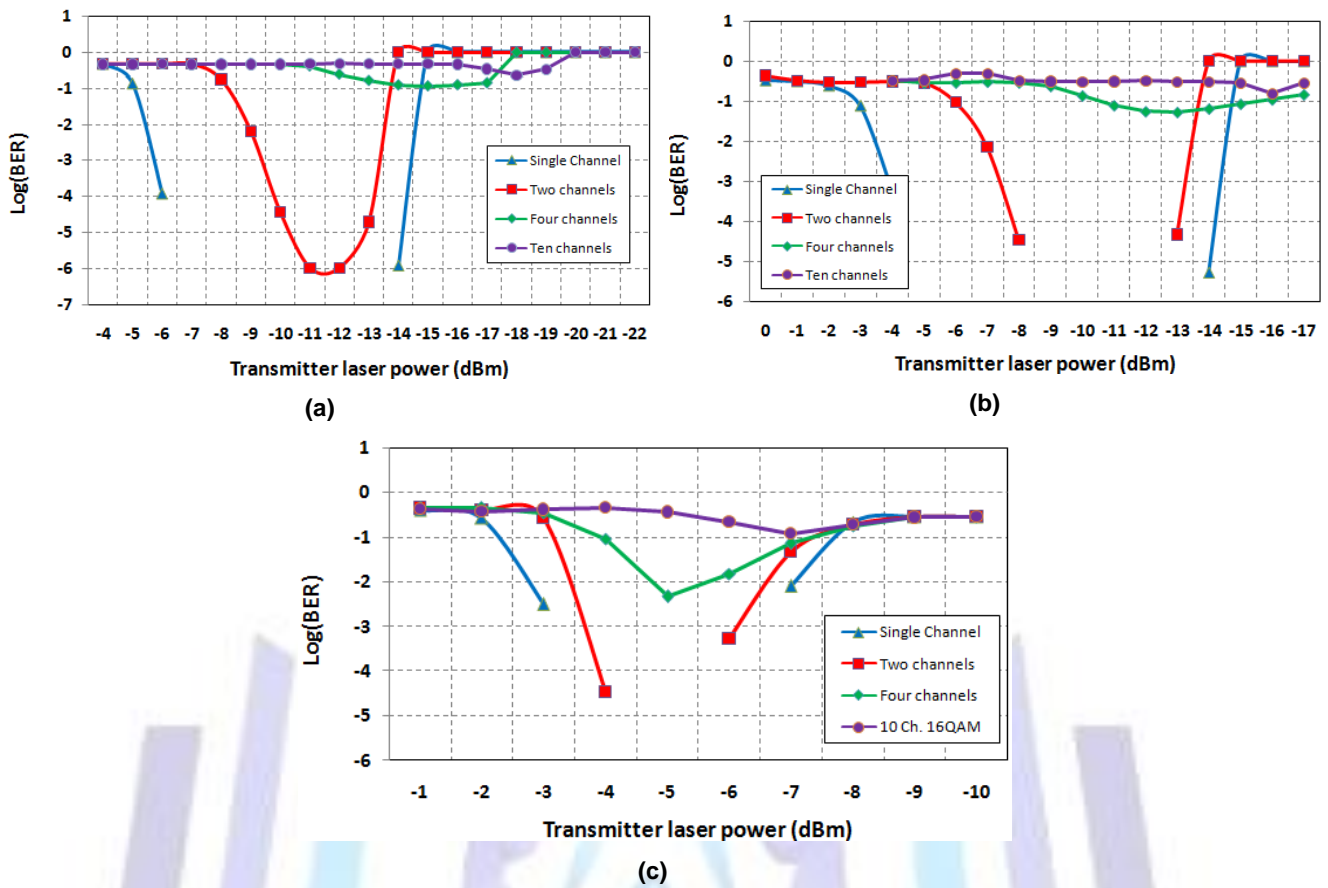


Fig. 16: BER versus the transmitter laser power for different modulation format. (a) BPSK for optical channel length of 29 spans. (b) QPSK for optical channel length of 12 spans. (c) 16-QAM for optical channel length 4 spans.

The high-level modulation format has a major role to increasing the spectral efficiency of the WDM system because it reduces the bandwidth of the modulated signal. However, it requires higher P_{opt} to keep the received BER within the specific level ($< 10^{-9}$) and thus will increase the fiber nonlinearity effect.

Figure 17 shows a summary of the results of Fig. 16 related to the three types of modulation formats which indicate the value of P_{opt} required for different number of channels.

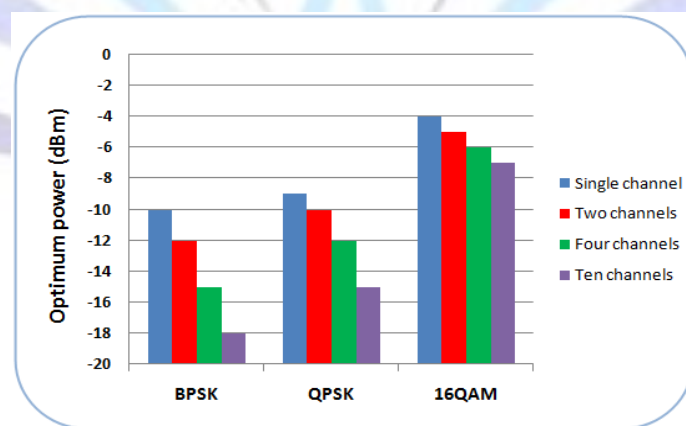


Fig. 17: Performance summary of the CO-OFDM WDM system operating with 29, 12, and 4 spans of BPSK, QPSK, and 16-QAM modulation formats, respectively.

Based on these results, the optimum power P_{opt} should be determined as the most appropriate value of the transmitter laser power required to get maximum transmission length while keeping the received BER within the required limit ($< 10^{-9}$) for different modulation formats. The suitability and feasibility of P_{opt} is chosen according to the following steps for given optical transmission length (N_{span})



- (i) Start the system as back to back ($N_{\text{span}} = 0$) configuration with -4dBm transmitter laser power (P_t) to test running without error.
- (ii) Increase the length of the transmission link by increasing the number of spans (N_{span}) and monitor the BER for each channel.
- (iii) Decrement the power of transmitter laser gradually (step by step) from (-4dBm) to (-25dBm) and find the BER of each step.
- (iv) Find the minimum BER from the data reported.
- (v) If minimum BER is less than 10^{-9} then increase N_{span} , else the transmitter laser power is the optimum value.
- (vi) Fixed P_{opt} .

The effect of number of multiplexed channel N on the value of P_{opt} is investigated for BPSK, QPSK, and 16-QAM modulation formats and the results are displayed in Figs. 18-20, respectively. These figures show the relationship between BER and transmitter laser power for different number of channels at the maximum transmission distance with BER less than 10^{-9} . Table 6 lists the variation of the optimum values of the transmitter laser power with number of multiplexed channels and modulation format.

Table6: Variation of the optimum transmitter laser power with different number of channels

Modulation Format	Number of channels	Optimum Power (dB)
BPSK	1	-10
	2	-11
	4	-11
	10	-11
QPSK	1	-13
	2	-13
	4	-12
	10	-12
16-QAM	1	-5
	2	-5
	4	-5
	10	-5

The relationship between the number of channels and the distance that can be reached by using P_{opt} while maintaining the BER less than 10^{-9} can be deduced from Figs. 21-23, for BPSK, QPSK, and 16-QAM signaling, respectively.

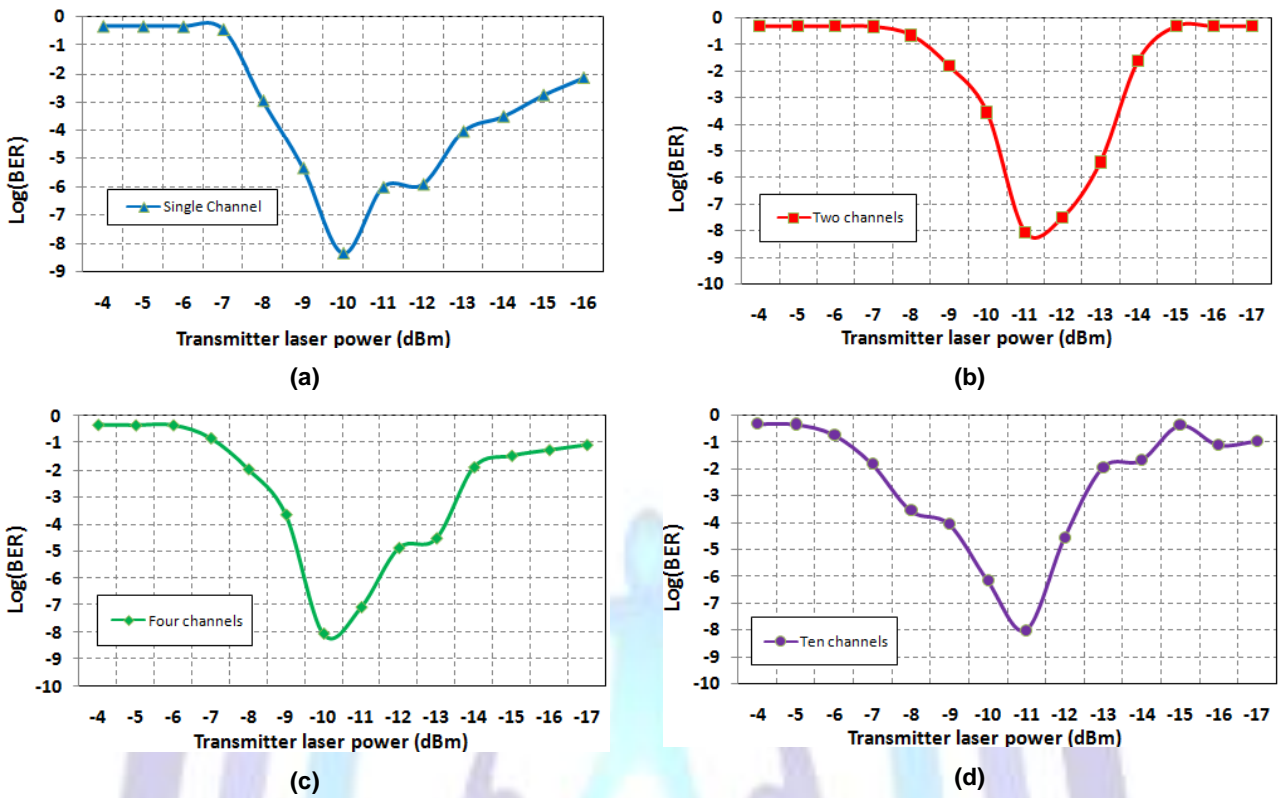


Fig. 18: BER versus transmitted laser power for BPSK system operating with maximum transmission length. (a) Single channel. (b) Two channels. (c) Four channels. (d) Ten channels.

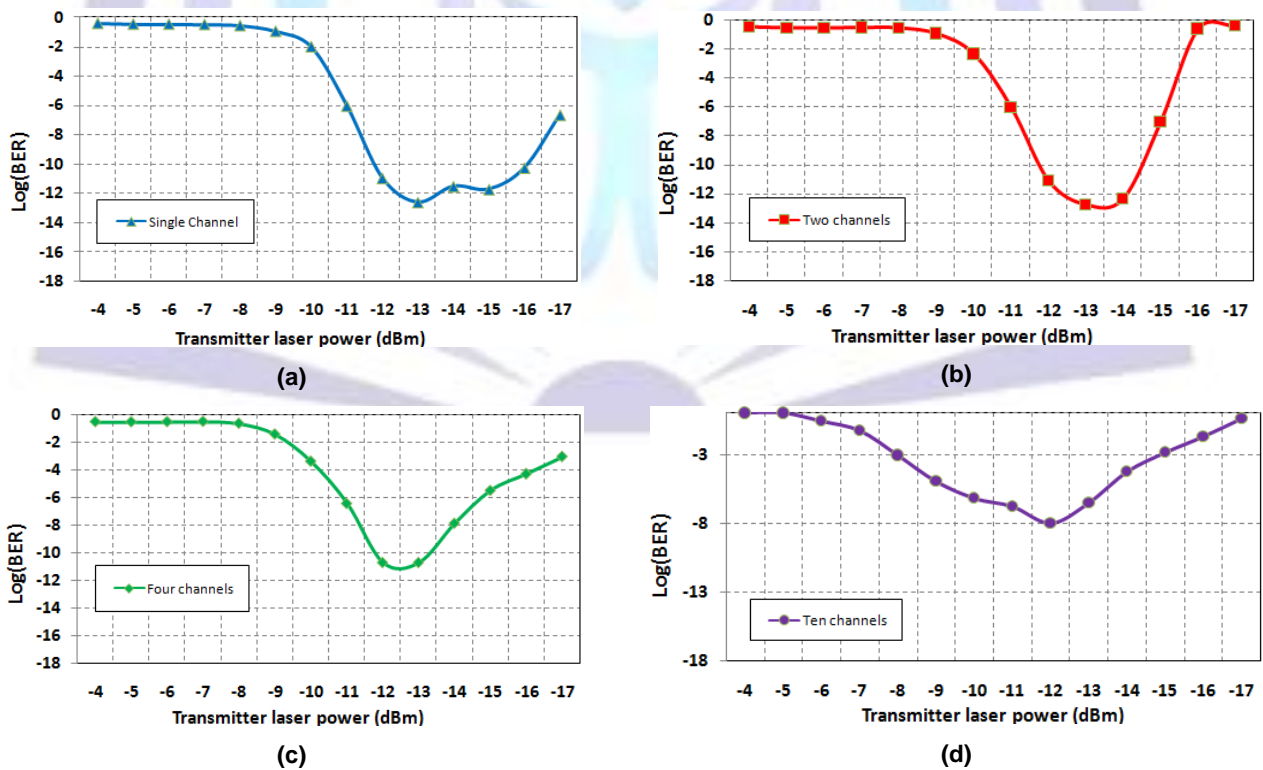


Fig. 19: BER versus transmitted laser power for QPSK system operating with maximum transmission length. (a) Single channel. (b) Two channels. (c) Four channels. (d) Ten channels.

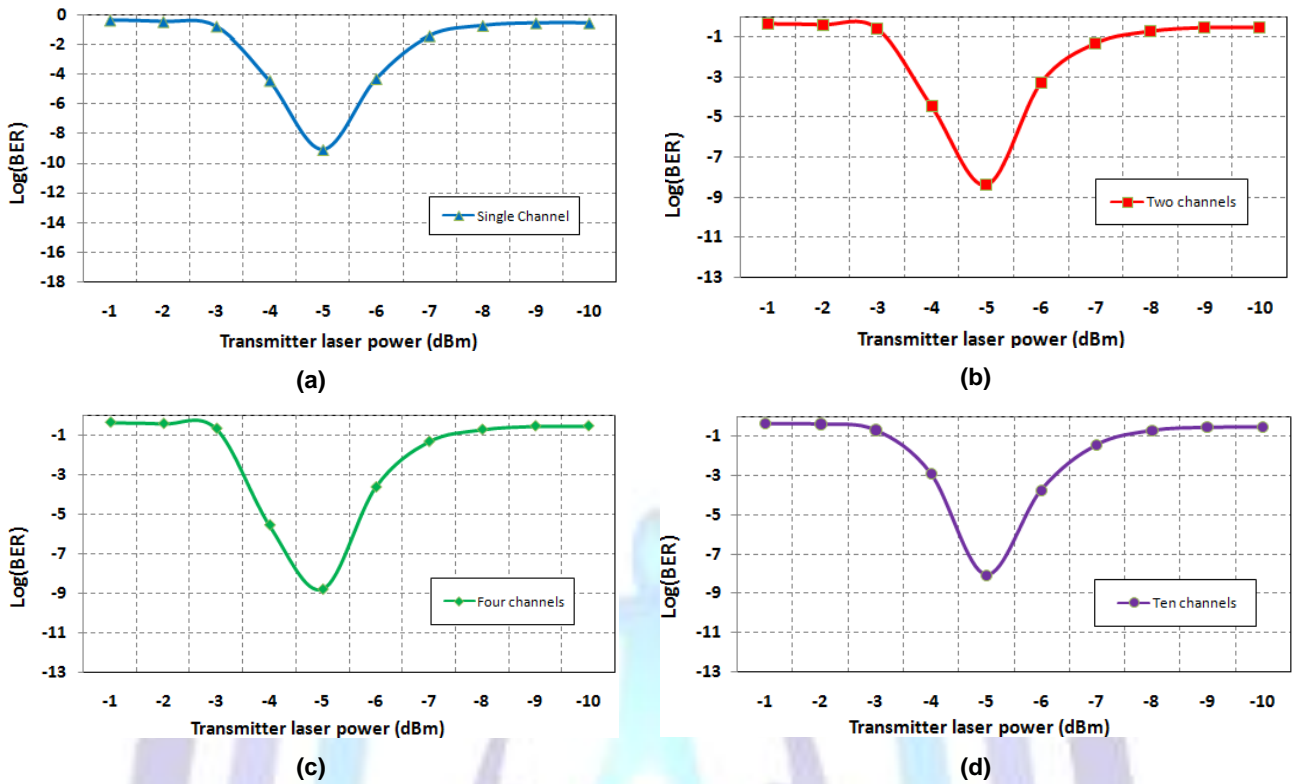


Fig. 20: BER versus transmitted laser power for 16-QAM system operating with maximum transmission length. (a) Single channel. (b) Two channels. (c) Four channels. (d) Ten channels.

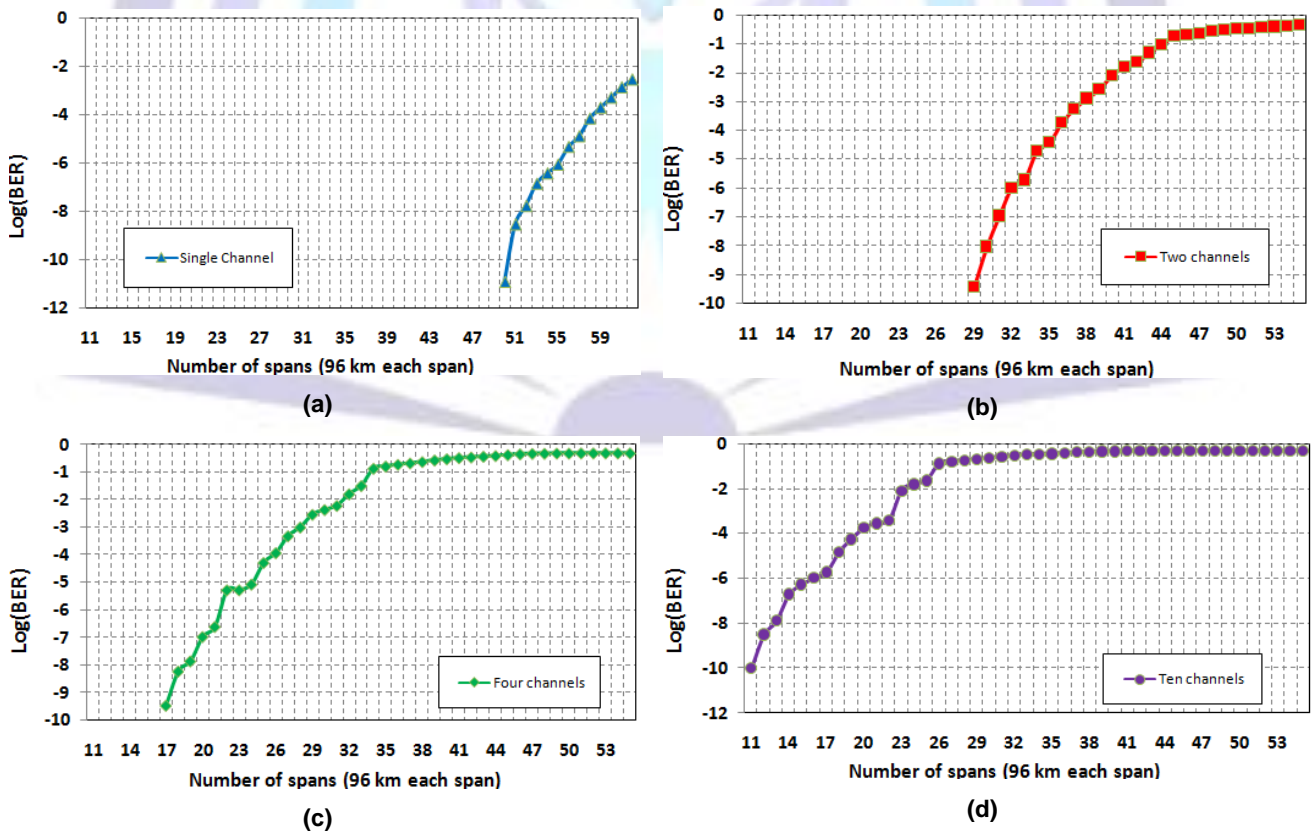


Fig. 21: BER versus number of spans for BPSK system operating with optimum power. (a) Single channel. (b) Two channels. (c) Four channels. (d) Ten channels.

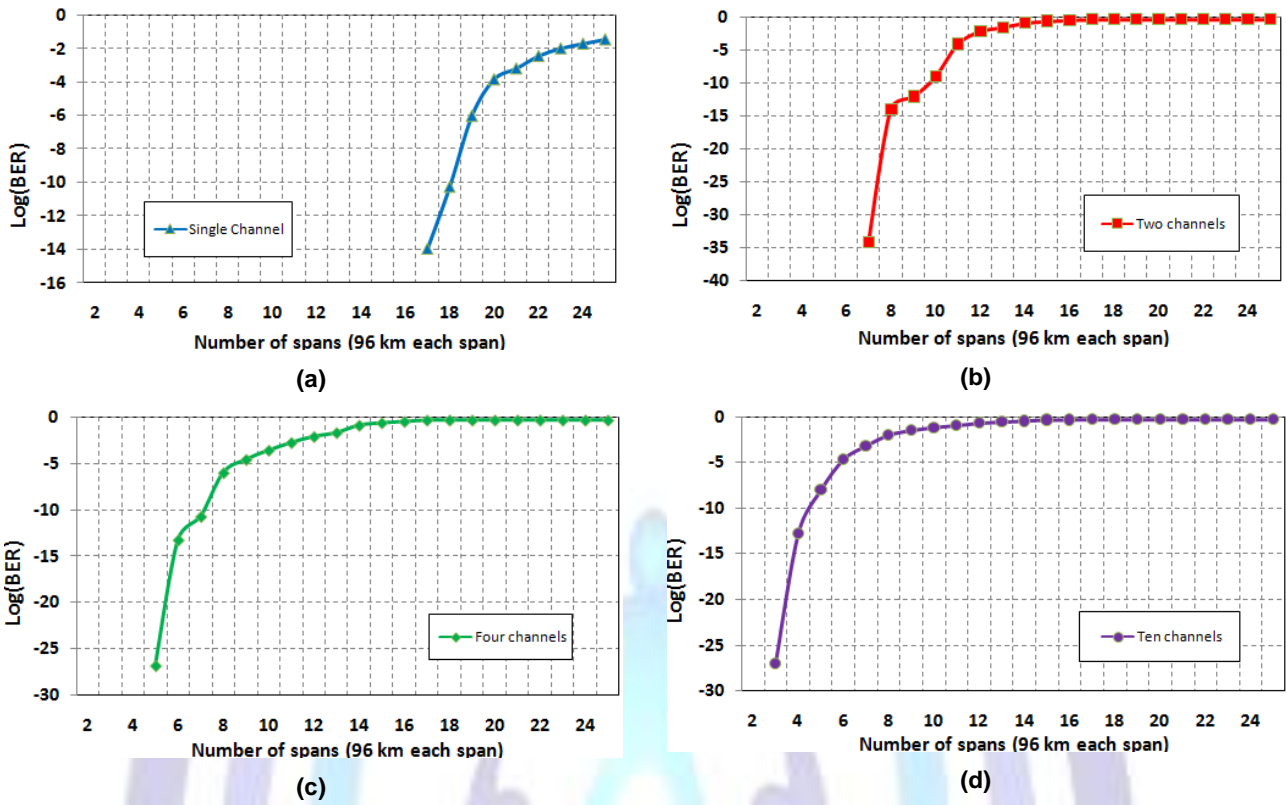


Fig. 22: BER versus number of spans for QPSK system operating with optimum power. (a) Single channel. (b) Two channels. (c) Four channels. (d) Ten channels.

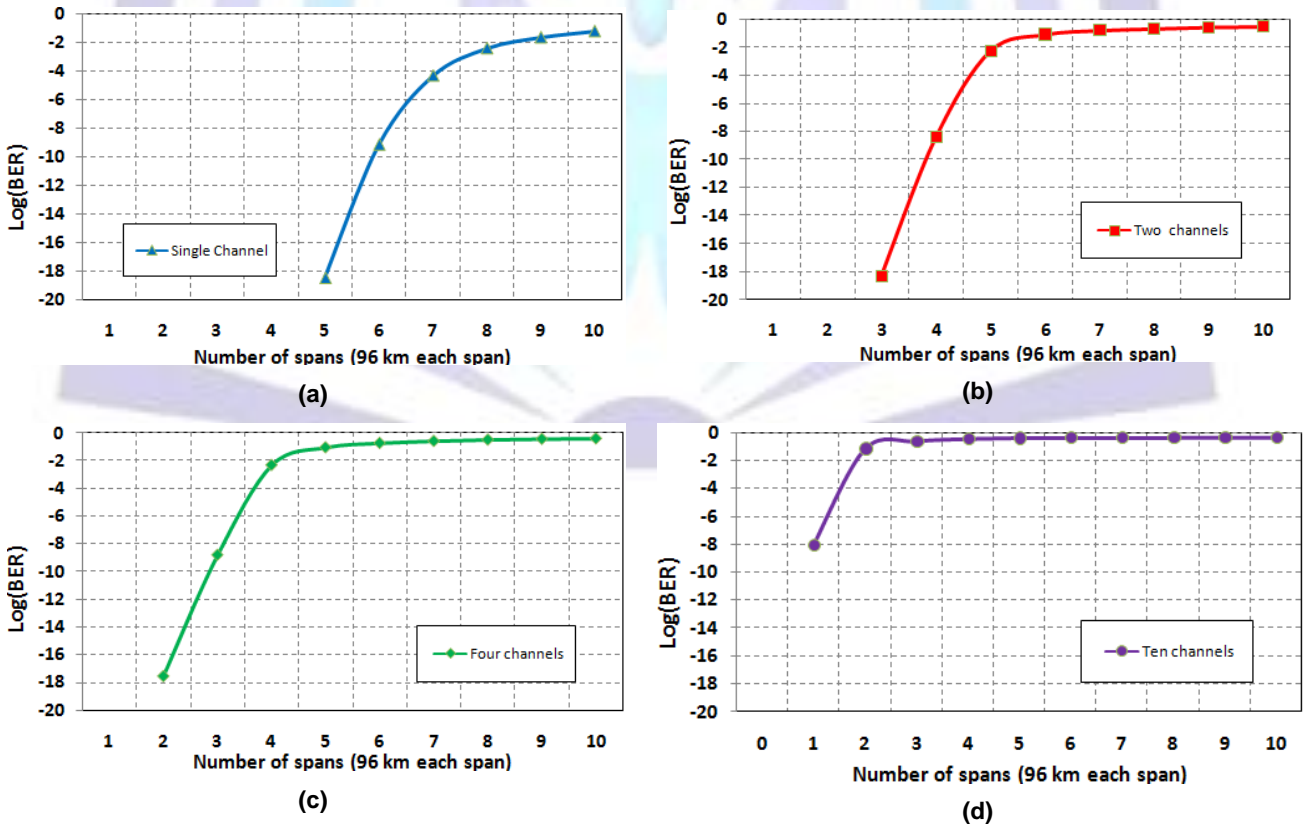


Fig. 23: BER versus number of spans for 16-QAM system operating with optimum power. (a) Single channel. (b) Two channels. (c) Four channels. (d) Ten channels.

Figure 24 shows summary of the results related to the three types of modulation formats as deduced from Figs. 21-23 and shows the maximum distance that can be reached while preserving BER at the most suitable value ($< 10^{-9}$).

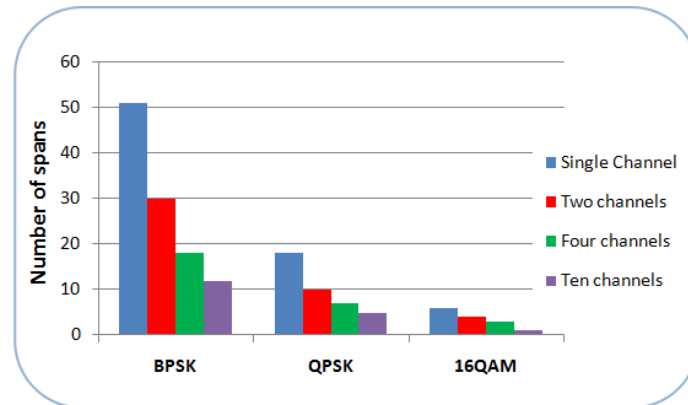


Fig. 24: Performance summary of the CO-OFDM WDM system operating with different modulation formats showing the maximum number of spans that can be used with the optimum power of each system.

It is worth to mention here that FWM is one of the phenomena that affect the performance of WDM system. The effect of FWM is more pronounced within the middle channels that are located in the middle of the total WDM signal spectrum. Figure 25 shows the variation of BER with channel number for a ten-channel WDM system operating with QPSK format. Note that channels 4, 5, and 6 have highest BER compared with other channels due to the effect of FWM.

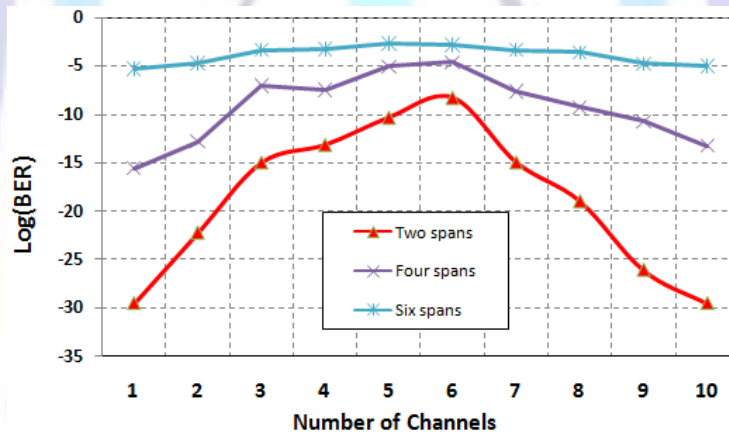


Fig. 25: BER of a ten-channel WDM system using QPSK format for different transmission link length with optimum power.

6. CONCLUSIONS

The performance of 100 Gb/s per channel wavelength-division multiplexing system incorporating both dual polarization and multiplexing techniques has been investigated. Emphasis has been placed on the effect of fiber nonlinearity for long-haul transmission systems. Simulation results related to conventional (single-polarization) counterparts has been also reported for comparison purposes. The main conclusions drawn from this study

- (i) To achieve a BER less than 10^{-9} in a conventional single-polarization system, the number of 96 km spans should be less than 325, 275, and 115 for BPSK, QPSK, and 16-QAM formats, respectively, in the absence of fiber nonlinearity. The presence of nonlinear fiber optics reduces the maximum allowable number of spans to 29, 23, and 8, respectively.
- (ii) To achieve a BER less than 10^{-9} in a dual-polarization system, the number of 96 km spans should be less than 305, 265, and 115 for BPSK, QPSK, and 16-QAM formats, respectively, in the absence of fiber nonlinearity. The presence of nonlinear fiber optics reduces the maximum allowable number of spans to 18, 14, and 6, respectively.
- (iii) To reduce the effect of fiber nonlinearity in a dual polarization WDM system, an optimum value of transmitter laser power should be selected to ensure maximum transmission distance with received BER $< 10^{-9}$.
- (iv) The optimum transmitter laser power is a function of number of multiplexed channels and modulation formats.
- (v) The high-level modulation format has a major role to increasing the spectral efficiency of the WDM system because it reduces the bandwidth of the modulated signal. However, it requires higher P_{opt} to keep the received BER within the specific level ($< 10^{-9}$) and this increases the fiber nonlinearity effect.



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