Order number:

Serial No:

People's Democratic Republic of Algeria

Ministry of Higher Education and

Scientific Research

Echahid Hamma Lakhdar University of El-Oued

Faculty of Technology Major: Electrical Engineering

End of study dissertation

Presented for graduation from

ACADEMIC MASTERS

In: Telecommunication

Specialty: Telecommunication systems

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Theme

Analysis and Compensation of Nonlinear Impairments in Optical Fiber communication systems

In front of the jury composed of:

Mr. Abdelkader Medjoudi	**….**	**President**
Mr. Abir Betka	**….**	**Examiner**
Mr. Narimane Hadjadji	**….**	**Supervisor**

2023-2024

بسم الله الرحمن الرحيم

Dedication (1)

To my family, the foundation upon which I stand, and to my friends, my chosen family, I dedicate this final graduation research. Your unwavering love, support, and companionship have been the guiding light throughout my academic journey. Mom and Dad, your sacrifices have paved the way for this moment of triumph. My siblings, your laughter and encouragement have been my constant companions. And my dear friends, your shared successes and challenges have made this experience truly meaningful. I am forever grateful for your presence in my life, and I offer this achievement as a testament to your dedication and the indelible mark you have left on my heart.

Bouafia Fatma Batoul

Dedication (2)

I dedicate this humble work to:

In memory of my father

To my mother

To my sisters

To my brother

To my dear family, may God grant them health and long life

All my friends

To those who had a great impact on my life

Djeradi Bilal

Acknowledgments

First and foremost, I express my deepest gratitude to the Almighty for granting me the strength, wisdom, and perseverance to complete this journey of knowledge and growth. His divine guidance has been a source of inspiration and comfort throughout this endeavor.

I would like to extend my heartfelt appreciation to my supervisor, Narimane HADJADJI, for her unwavering support, invaluable guidance, and mentorship during the course of this project. Her expertise, encouragement, and constructive feedback have been instrumental in shaping my research and academic development.

To the faculty members, mentors, and all those who have contributed to my growth and learning, I offer my sincere thanks for their dedication and commitment to nurturing young minds and fostering a culture of academic excellence.

This project would not have been possible without the collective support and encouragement of all those who have touched my life in various ways. I am truly grateful for the opportunity to learn, grow, and contribute to the field of systems of the wire-wireless telecommunication.

Thank you all for being a part of this transformative journey.

Abstract

Abstract:

Efficient and dependable communication systems are critical due to the increasing demand for high-bandwidth applications such as high-definition video streaming and cloud computing. Optical communication technologies have become the fundamental infrastructure of contemporary networks, facilitating the transfer of large quantities of data (such as high-definition video files) over long distances.

Nevertheless, these systems are vulnerable to non-linear phenomena that result from the interaction between light and the optical fiber. The presence of non-linear effects can cause signal distortion, resulting in higher bit error rates (BER) and eventually degrading the performance of the system.

The goal of this research project is to find ways to use digital backpropagation (DBP) to improve optical communication systems that have non-linear distortions. The objective is to reduce the negative impacts of non-linearity and enhance the efficiency of the system for transmitting high-speed data.

Keywords: optical coherence system, Kerr effects, DBP algorithm, nonlinearity compensation.

ملخص:

تكتسي نظم الاتصالات الكفؤة والموثوقة أهمية حاسمة بسبب تزايد الطلب على التطبيقات ذات النطاق الترددي العالي مثل تدفق الفيديو العالي الوضوح والحوسبة السحابية. وقد أصبحت تكنولوجيات الاتصالات البصرية البنية الأساسية للشبكات المعاصرة، مما ييسر نقل كميات كبيرة من البيانات (مثل ملفات الفيديو العالية الوضوح) على مسافات طويلة .

ومع ذلك، فإن هذه النظم معرضة للظواهر غير الخطية الناجمة عن التفاعل بين الضوء والألياف البصرية. ويمكن أن يؤدي وجود آثار غير خطية إلى تشويه الإشارات، مما يؤدي إلى ارتفاع معدلات الخطأ بالبت، ويؤدي في نهاية المطاف إلى تدهور أداء النظام .

والهدف من هذا المشروع البحثي هو إيجاد سبل لاستخدام الارتجاع الرقمي لتحسين نظم الاتصالات البصرية التي تنطوي على تشوهات غير خطية. والهدف من ذلك هو الحد من الآثار السلبية لعدم الخط وتعزيز كفاءة نظام نقل البيانات العالية السرعة .

الكلمات الرئيسية: نظام التماسك البصري، آثار كير، خوارزمية الانتشار الرقمي الخلفي ، التعويض غير الخطي .

Résumé :

Les systèmes de communication efficaces et fiables sont essentiels en raison de la demande croissante d'applications à large bande, telles que le streaming vidéo haute définition et le cloud computing. Les technologies de communication optique sont devenues l'infrastructure fondamentale des réseaux contemporains, facilitant le transfert de grandes quantités de données (telles que les fichiers vidéo haute définition) sur de longues distances.

Néanmoins, ces systèmes sont vulnérables aux phénomènes non linéaires résultant de l'interaction entre la lumière et la fibre optique. La présence d'effets non linéaires peut provoquer une distorsion du signal, entraînant des taux d'erreur de bits plus élevés (BER) et dégradant finalement les performances du système.

L'objectif de ce projet de recherche est de trouver des moyens d'utiliser la rétropropagation numérique (DBP) pour améliorer les systèmes de communication optique qui ont des distorsions non linéaires. L'objectif est de réduire les effets négatifs de la non-linéarité et d'améliorer l'efficacité du système de transmission de données à grande vitesse.

Mots clés : système de cohérence optique, l’effet Kerr, algorithme DBP, compensation de la non-linéarité.

Summary

Summary

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Nonlinear compensation of an optical transmission chain by digital back propagation technology

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List of Abbreviations

Acronyms	*Signification Anglo-Saxon*
SMF	Single mode fiber
WDM	Wavelength Division Multiplexing
LO	Local oscillator
ADC	Analog-to-digital converter
FEC	Forward error corrector
PRBS	Pseudo random binary sequence
ISI	Inter symbol interference
DB	Duo binary
RZ	Return to zero
CSRZ	Carrier suppressed return to zero
MZI	Mach Zehnder interferometer
MZM	Mach Zehnder modulator
PDM	Polarization division multiplexing
SDM	Space division multiplexing
PBS	Polarization bean splitter
SRS	Stimulated Raman scattering
SBS	Stimulated Brillion scattering
EDFA	Erbium doped fiber amplifier
DSP	Digital signal processing
DC	Direct current
IF	Intermediate frequency
SPM	Self-phase modulation
XPM	Cross phase modulation
FWM	Four wave mixing
QPSK	Quadrature phase shift keying
QAM	Quadrature amplitude modulation
NLSE	Nonlinear Schrodinger equation
SSFM	Split step Fourier method
DBP	Digital backpropagation

General Introduction

General Introduction

The ever-increasing demand need for fast data transmission requires ongoing progress in communication technologies. Optical communication systems play a vital role in this landscape, enabling the transmission of massive data volumes across vast distances. However, a significant challenge lies in overcoming limitations imposed by physical phenomena within optical fibers. These limitations, known as non-linear effects, can degrade signal quality, ultimately limiting the achievable transmission capacity and reach.

This master's thesis investigates whether digital backpropagation (DBP) can reduce the destructive effects of non-linearity in high-speed optical communication systems. DBP method is a computational technique that simulates the signal distortions occurring during propagation within the fiber optical channel. By incorporating this information into the signal processing algorithms, DBP aims to compensate for these distortions and improve overall system performance.

This thesis is utilized the optical system called a PDM-0.3RZ-QPSK system that uses Polarization Division Multiplexing (PDM) and 0.3 Return to Zero- Quadrature Phase-Shift Keying (QPSK) modulation. The research explores the impact of Intrachannel non-linear effects on this system, particularly self-phase modulation (SPM).

The core of this work is to assess the effectiveness of DBP in mitigating these non-linear impairments. The research will involve numerical simulations to evaluate system performance for various parameters, including symbol rates and transmission distances. We will use critical metrics like bit error rate (BER) and Q-factor to quantify the improvements in signal quality and transmission fidelity achieved through DBP.

The remainder of this thesis follows this structure:

- Chapter 1 provides a background on coherent optical communication systems, including their components and the various degradations encountered during signal transmission through optical fibers.
- Chapter 2 explores the concept of DBP for non-linearity compensation in the coherent optical system.
- Chapter 3 presents a detailed performance analysis of the PDM-0.3RZ-QPSK coherent optical system with and without DBP implementation. The study will consider different symbol rates and evaluate the impact of DBP on achievable transmission distances.

Finally, conclude the thesis by summarizing the essential findings and discussing their potential.

Chapter 1:
Coherent Optical System

I.1 Introduction

The evolution of optical communication is a story of innovation and constant challenges overcome. This technology continues to play a critical role in global telecommunication infrastructure, enabling high-speed, long-distance data transmission that underpins the development of the internet, cloud computing, and many other critical applications.

Coherent optical technologies have greatly revolutionized optical communications. They have enabled the transmission of large amounts of data over long distances. These systems utilize advanced modulation techniques and digital signal processing to extract and decode information from optical signals. By employing coherence principles, these systems can tackle specific limitations that are frequently encountered in conventional optical systems, such as dispersion and noise. Coherent optical systems are now the essential foundation of modern telecommunication networks due to their exceptional ability to transmit data at high rates across long distances. Now they are crucial in enabling the introduction of new technologies such as 5G.

This chapter will examine coherent optical systems basic concepts, parts, and system performances.

I.2 The evolution of Optical Communication

Optical communication has become the go-to technology for high-speed, long-distance data transmission. But this success is the result of a long journey and constant innovation. Let's explore the major milestones in this fascinating evolution. [1][2]

Humble Beginnings (1960s):

- The invention of the laser and low-attenuation optical fibers paved the way for transmitting light signals over longer distances. However, early systems suffered from high attenuation (signal loss), limiting their range.

The Age of Single-Mode Fiber and Optical Amplifiers (1970s-1980s):

- The development of single-mode fibers (SMF), allowing for more efficient light propagation, was a major turning point.
- The invention of optical amplifiers made it possible to compensate for signal attenuation and significantly extend the reach of optical communication.

The Multiplexing Boom and the Rise of the Internet (1990s-2000s):

- The arrival of wavelength-division multiplexing (WDM) revolutionized transmission capacity. This technique allows for transmitting multiple signals simultaneously on a single optical fiber, dramatically increasing data rates.

- The explosive growth of the internet propelled optical communication to the forefront of global telecommunication infrastructure.

A Race for Efficiency and Performance (2000s-Present):

- Research has focused on improving dispersion compensation techniques to counteract signal distortion effects over long distances.
- The emergence of new modulation formats and coding techniques optimizes bandwidth usage and achieves ever-higher transmission speeds.

Looking Ahead:

- Exploration of novel optical fibers, such as hollow-core fibers and multi-core fibers, paves the way for even greater transmission capacities.
- Research on quantum optical communication promises ultra-secure transmissions and speeds that could surpass the limitations of classical communication.

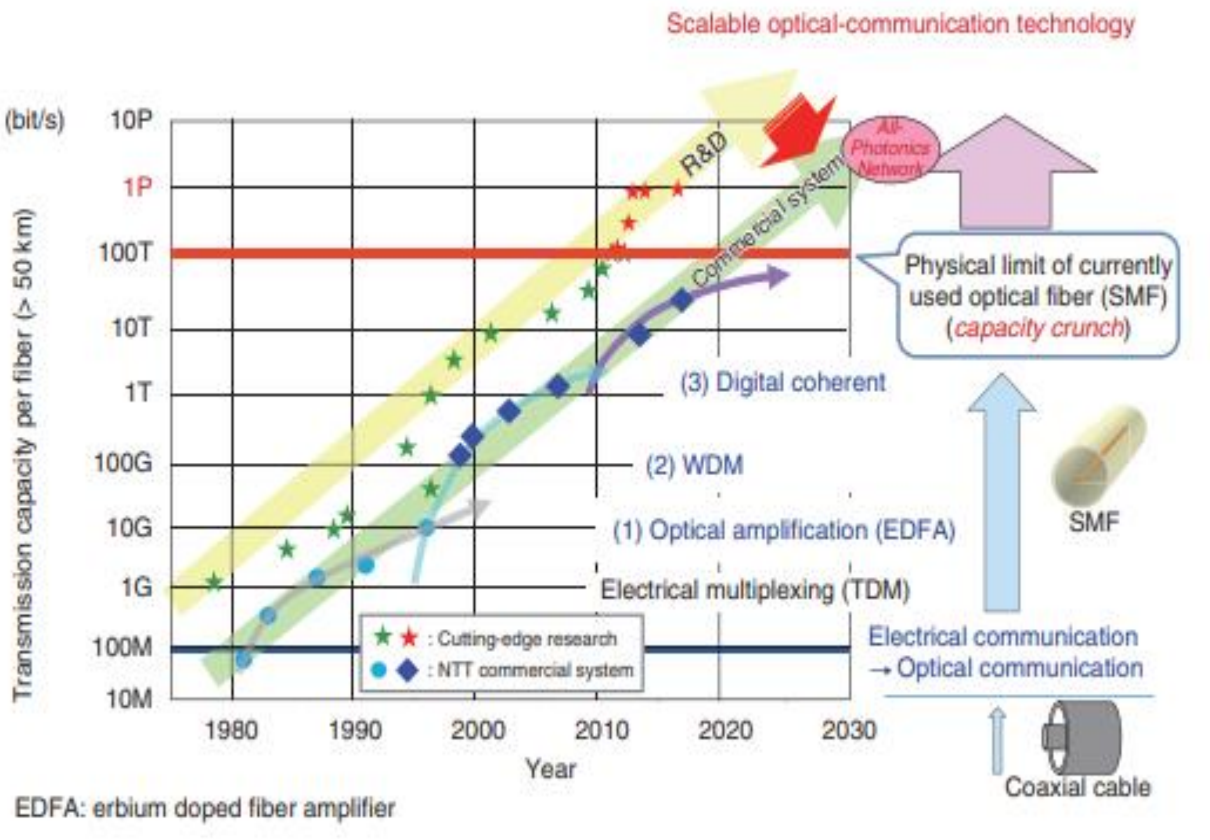


***Figure I.1**: Evolution of optical communication.* [3]

Figure 1.2 shows the global fiber optic transmission system linkage, which transports 99 percent of all global telecommunication traffic.

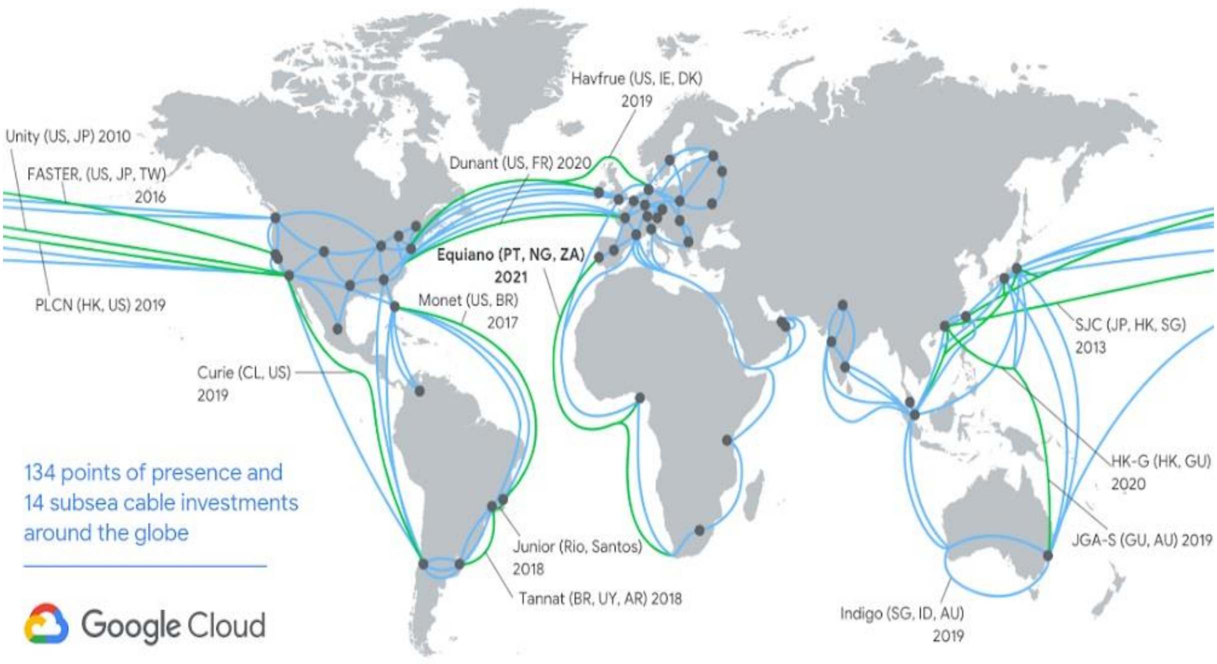


***Figure I.2**: International network of underwater optical systems around the world.* [4]

I.3 Optical fiber capacity crunch: challenges and solutions

The escalating demand for data transmission is rapidly outpacing the capabilities of traditional optical fiber networks, leading to a critical situation known as the optical fiber *capacity crunch* [5]. It pertains to the restriction on transferring larger quantities of data over current carrier media. The capacity crunch problem in communication networks can be attributed to multiple factors.

The main reason for the delay in implementing new connections and maintaining old ones is the ships' inability to deploy fiber optic cables. Another worry relates to the technological constraints of carrier mediums, such as the nonlinear Shannon limit, which sets an upper limit on the data transmission capacity of a fiber optic connection as illustrates in Figure 1.3 [6].

The issue of capacity crunch is further influenced by social variables such as energy consumption and net neutrality, which pose challenges relating to the wireless spectrum and the deployment of 5G signals.

Researchers have devised numerous alternatives to overcome the limitations imposed by the physical constraints on bandwidth capacity. The techniques encompassed in this category are wavelength division multiplexing (WDM), space division multiplexing (SDM), and signal pre-distortion in fiber optic connections [7].

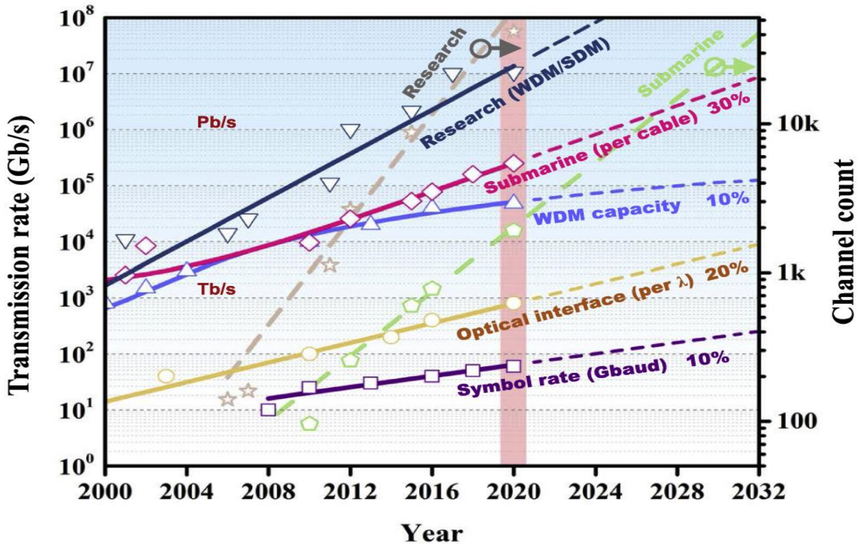


***Figure I.3**: The development techniques.* [8]

We anticipate that the Internet of Things and fifth-generation mobile communication networks (5G) will continue to drive exponential data traffic growth. The growth rate for data traffic is approximately 1.4 times yearly.

I.4 Fundamentals of coherent optical systems

The figure 1.4 displays the configuration of a coherent optical system. A coherent system has three essential pieces: the transmitter block, the transmission channel, and the reception block. In the transmitter, the transmitter laser is modulated by data bits. Then, an optical fiber is employed in the transmission block to convey the signal. After this, the signal is mixed with an LO laser at the optical front end of the receiver, and the optical signal is transformed into an electrical signal using balanced photodetectors. The electrical front end comes next. Analog-to-digital converters (ADCs) are devices that translate analog electrical signals into digital signals. Digital signal processing is then utilized to process and demodulate the signal [9].

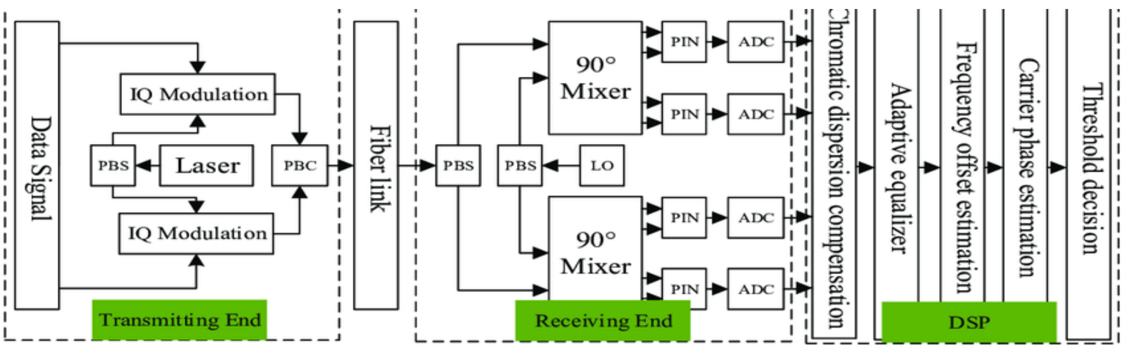


***Figure I.4**: Coherent optical communication system structure diagram.* [10]

I.4.1 Transmitter

First, the information transmitted from the source is transformed into a series of binary elements. The bit rate D is defined by the number of binary elements transmitted per unit of time and expressed in bit/s. Then, encode the information bits by adding the redundancy bits of the error correcting codes (FEC) to the binary sequence in order to be able to correct errors.

This step is followed by mapping these bits to predefined symbols and producing a time-domain digital waveform. A symbol encodes one or more bits depending on the modulation format used. Finally, in the optical modulation phase, the data must be written on a carrier to propagate in the transmission channel. [11]

I.4.2 Bit sequence

Bit sequences are essential for digital information transfer in coherent optical systems. These sequences, which increase spectral efficiency and data rates, are frequently called multiple-bits-per-symbol or pseudo-random bit sequences (PRBS). They represent the data information and are usually created with a specified period and bit rate.

PRBS reduces phase noise and intersymbol interference (ISI), two prevalent issues in optical communication systems. They are also essential for the receiver's error correction procedure since they allow for accurate data recognition and decoding transmission. [12]

I.4.3 Generation of electrical signals

Encoding the data into binary digits (0s and 1s) is the initial stage in producing electrical signals; the bits are translated into the modulation format's symbols. The symbol sequence is independent and symmetrically distributed to the pulse's form to provide an oversampled representation with the same information. [11]

$$\mathbf{u_E(t) = \sum_{-\infty}^{\infty} S_k\, g(t - kT_s)} \quad \text{(I.1)}$$

Where sk is the symbol at the instant, kT_S and g(t) is the form of the pulse, the bandwidth of the obtained signal is controlled by the pulse shaping filter.

Many optical pulse types, including Duobinary (DB), Nyquist, Return to Zero (RZ), and Carrier Suppressed Return to Zero (CSRZ), can be considered in the theoretical analysis of optical transmission. These pulse shapes are crucial for modulating optical signals to carry data, and they are employed in a variety of optical communication systems to ensure efficient and distortion-free information transmission. [11]

I.4.4 The laser

The transmitter mainly comprises a laser (Light Amplification by Stimulated Emission of Radiation, usually a diode laser) that continuously emits light at a specific wavelength and power. A light signal's power is expressed in milliwatts (mW), but in practical applications, it is most often expressed in decibels-milliwatts (dBm). [11]

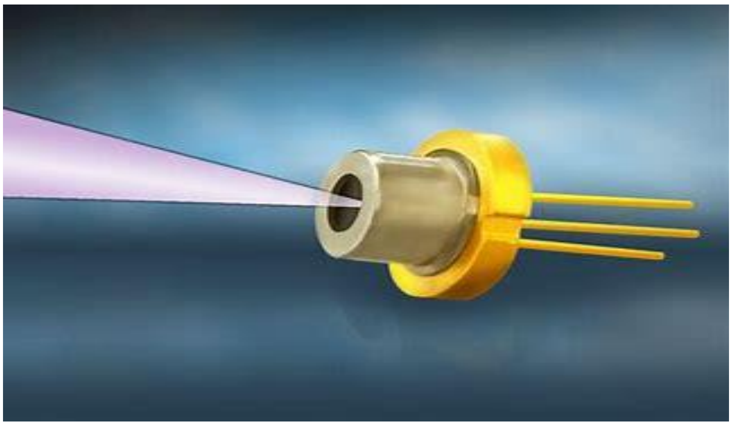


Figure I.5: *Scheme of a laser diode.* [13]

I.4.5 The external modulation

It is preferable to use an external modulator to avoid the chirp (a parasitic phase modulation of the optical signal depending on the pump signal power) in direct modulation and to use more varied modulation patterns with a bit rate greater than 10 Gbit/s over long distances. External modulation involves sending electrical data over a continuous optical signal. It is obtained by selectively adjusting the laser's light beam at its output and reducing the supply current at the laser's input.

In coherent systems, the standard technique for external modulation is to use a Mach-Zehnder Interferometer (MZI) and electro-optic cells based on lithium niobate (LiNbO3) due to the excellent electro-optic properties of the material (shallow propagation losses at telecommunications wavelengths, high electro-optic coefficients, and low coupling losses between an optical fiber and LiNbO3 waveguides).

The Mach-Zehnder modulator's (MZM) fundamental principle is based on the electro-optical effect that allows one or both of the interferometer's braces to change their index of refraction by applying an electrical field to them.

The schematic representation of a Mach-Zehnder modulator is shown in figure 1.6. A difference in potential leads to a dispersion between the two waves propagating in the two arms of the Mach-Zehnder interferometer, each of which receives half of the initial light source power. Then, the two nodes recombine and give rise to interferences, which can be either constructive (highest transmitted intensity) or destructive (lowest transmitted intensity). [11][9]

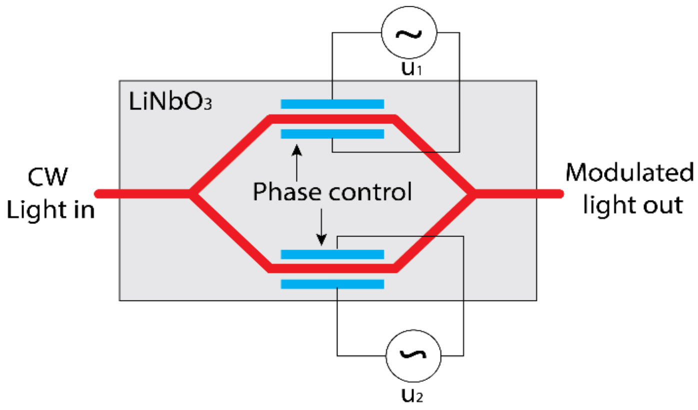


Figure I.6*: Scheme of principle of a Mach-Zehnder modulator*[14].

I.4.6 Multiplexing techniques

Multiplexing techniques are used to increase spectral efficiency in optical transmission. *Spectral efficiency* is a value used to evaluate the efficiency with which information is transferred in a given bandwidth of the channel.

The most commonly used types of multiplexing in long-distance transmission systems (terrestrial and submarine) are wavelength division multiplexing (WDM), polarization division multiplexing (PDM), and space division multiplexing (SDM).[11][15]

I.4.6.1 wave-length division multiplexing WDM

WDM is a type of optical multiplexing that enhances bandwidth. It multiplexes various optical carrier signals into one optical fiber at different wavelengths. Every signal at WDM wavelengths is independent of speed and protocol. Thanks to WDM technology, a single optical fiber can support simultaneous bidirectional communications. WDM reduces the required fibers, increasing bandwidth and lowering networking costs. [15]

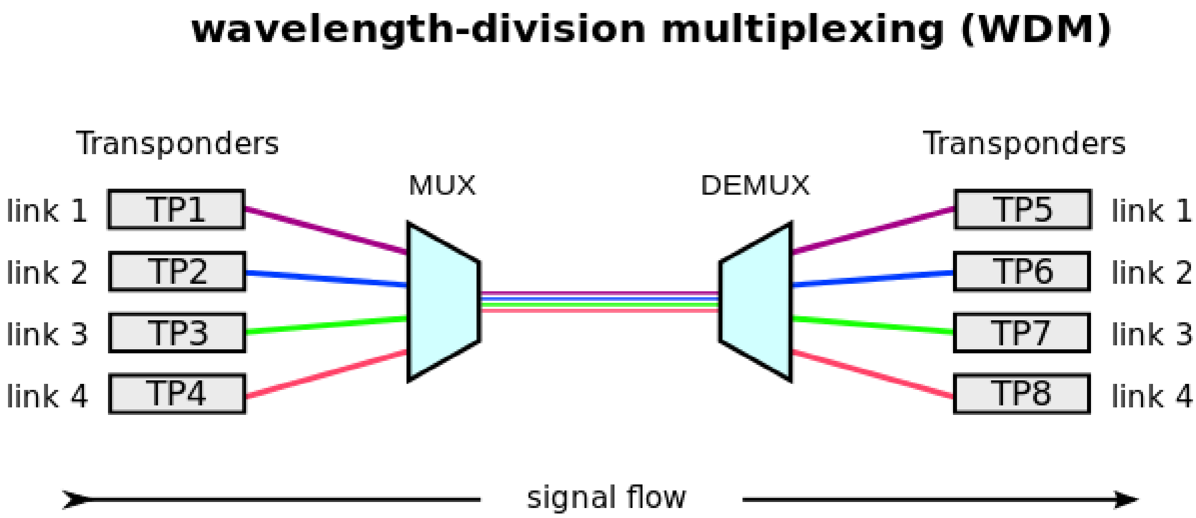
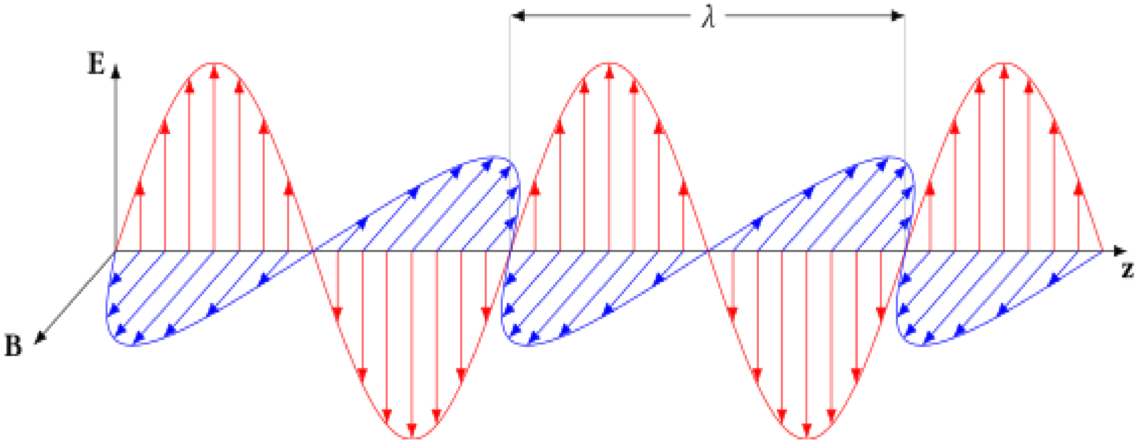


Figure I.7: *Principle work of the WDM.* [16]

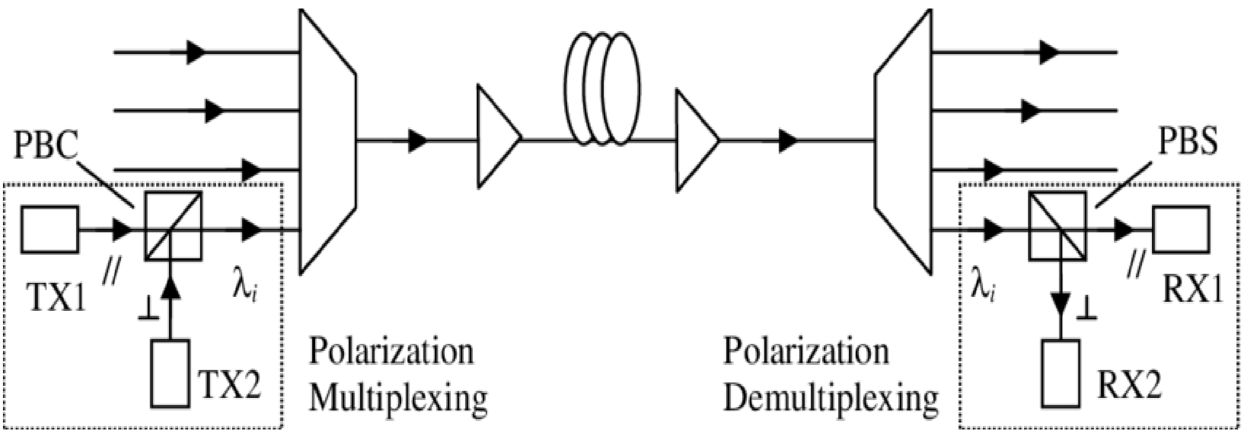
WDM systems can be classified according to the normalized frequency spacing factor. Currently, there is talk of quasi-Nyquist WDM, Nyquist WDM, and super-Nyquist WDM systems where channel spacing is below 25 GHz. These three transmission systems are proposed for the next generation of WDM systems to achieve 400Gbps or 1Tbps as the transmission speed. [11]

I.4.6.2 Polarization division multiplexing PDM

Polarization division multiplexing (PDM) is performed at the emission level by using the two fundamental orthogonal modes of the single-mode optical fiber to double the spectral efficiency of transmission. The figure 1.8 illustrates a polarization division multiplexing (PDM) system.



(a)



(b)

***Figure I.8**: Two orthogonal polarization, PDM principal.* [17][18]

The structure of this multiplexing scheme consists of a polarization beam splitter (PBS) to separate the emitted laser field into two orthogonal polarized fields. After modulation, these two signals are combined again using an optical combiner (PBC). To recover the transmission data, the digital processing block must perform the function of demultiplexing the multiplexed signals in polarization. [15]

I.5 Optical channel and propagation in optical fiber

The path connecting the transmitter and receiver is the optical channel, which in optic communications is a fiber .these ultra-thin glass or plastic wires, have become the backbone of modern communications. Their ability to transmit light signals over long distances with minimal loss makes them indispensable tools for the Internet, telephony, and many other applications. Optical amplifiers are required to give the receiver enough power across very long lines.

Another significant characteristic is the propagation time of the waves moving via the optical channel. A signal propagating along a fiber typically distributes its power along multiple ray routes and encompasses a range of fiber optic frequencies. As a result, the propagation signal gets distorted. This distortion manifests as the pulses spreading and deforming in a digital system. The spreading gets so bad that neighboring pulses blend and lose their identity as distinct information. [19]

I.5.1 Structure of optical fiber

Optical fibers are thin and flexible strands of glass or plastic that transmit light signals over long distances. They are used in a wide variety of applications, including telecommunications, data transmission, and medical imaging.

An optical fiber consists of three concentric pieces: the core, the cladding, and the outer coating, often known as the buffer.

Core: the interior component that carries light and has a high index of refraction.

Cladding: the central layer surrounds the core, keeping light within. Its index of refraction is lower.

Buffer: the exterior layer acts as a "shock absorber" to shield the cladding and core from harm. To shield the fiber from the outside elements, the coating typically consists of one or more layers of a plastic substance. Occasionally, the coating is enhanced with metallic sheaths to provide further physical protection. [19]

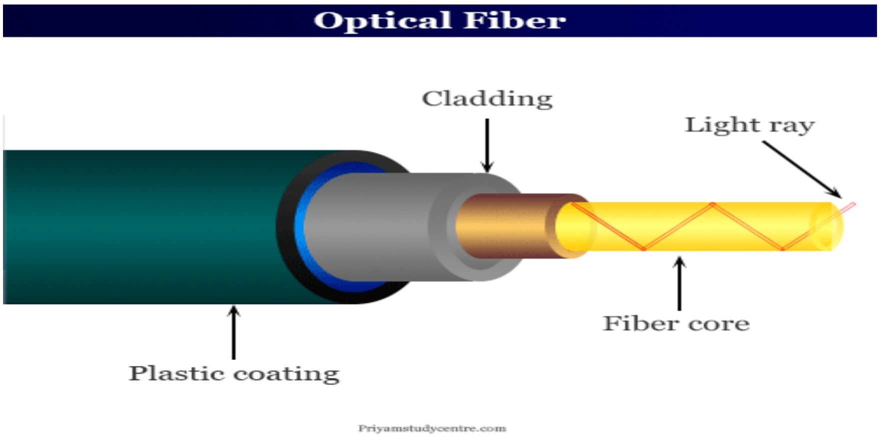


Figure I.9*: The structure of the optical fiber.* [20]

When light is introduced into the fiber optic core, it is reflected into the core when it reaches the core-to-cladding interface at an angle more significant than the critical angle. Since the incident and reflection angles are equal, the light ray continues to zigzag down the length of the fiber. The core contains the imprisoned light. When light enters the cladding at an angle smaller than the crucial one, it gets lost from the interface.

Step-index fibers are those whose refractive index at the core-cladding interface abruptly changes and whose index remains constant throughout.

Step-index fibers have core sizes ranging from 100 mm to 1000 mm. They are a good fit for applications needing high power densities, such as providing laser power for industrial and medical uses.

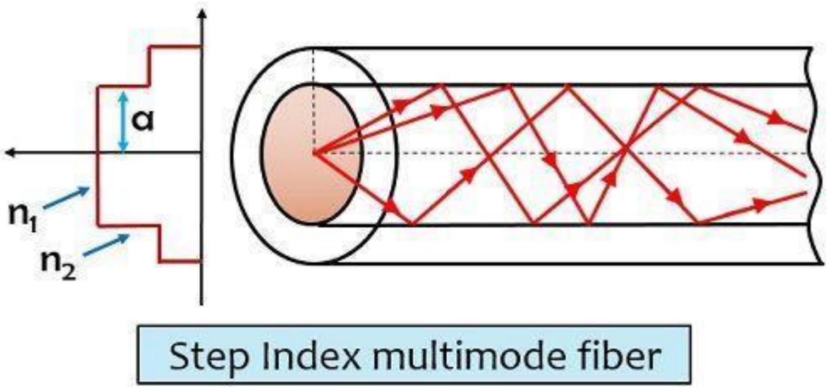


Figure I.10*: Step index multimode fiber, $n_1$core refractive index, n_2 cladding refractive index.* [21]

Step-index multimode fibers can trap light at a wide range of entrance angles because each mode in the fiber has a unique entrance angle. As a result, each mode takes a unique course through the fiber. Velocity varies across different spreading modes. An optical pulse starts to spread as it moves through a multimode cable. Over time, pulses that arrive at different times will eventually overlap. This reduces the amount of distance that the fiber can carry data. Multimode step-index fibers are not ideal for communications and data transfer.

The index of refraction of the core in a multimode graded-index fiber falls with increasing radial distance from the center of the core. As a result, light moves more quickly toward the core's perimeter than it does toward its center. Different modes follow curved routes that have almost comparable trip times, which significantly decreases the propagation of optical pulses.

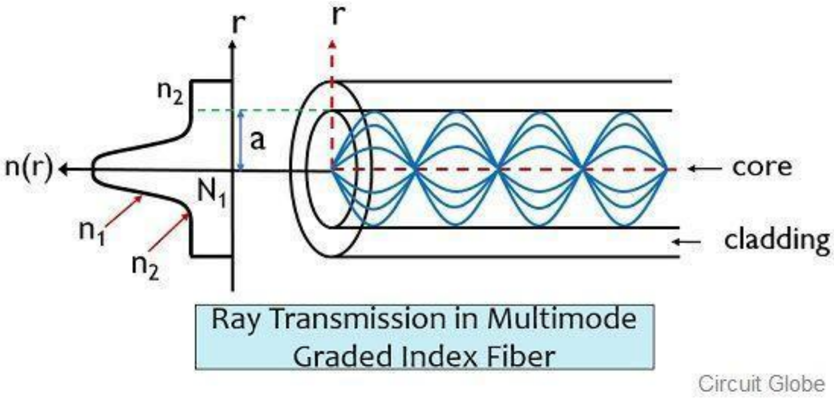


Figure I.11*: Multimode graded index fiber*. [22]

A single-mode fiber eliminates the need for various velocities for distinct modes and allows light to travel along its center. Since a single-mode fiber is substantially thinner than a multimode fiber, geometrical optics no longer applies to its analysis. Core diameters typically range from 5 to 10 mm.

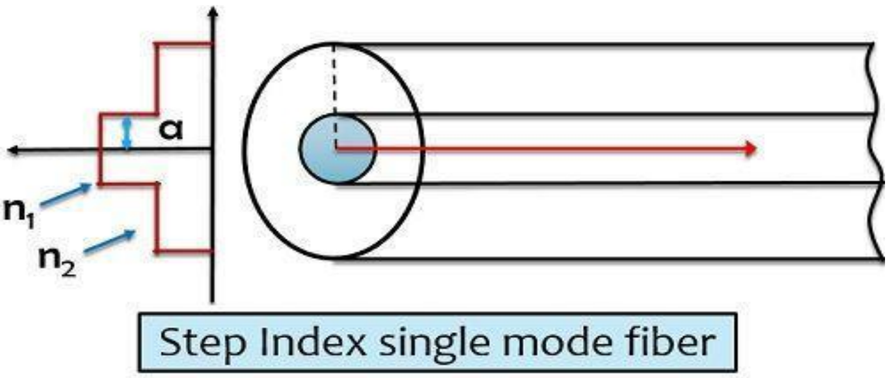


Figure I.12*: Step index single mode fiber*. [21]

I.5.2 Wave propagation equation

I.5.2.1 Maxwell's equation

Like other electromagnetic processes, the Maxwell equations control the propagation of optical fields in fibers. These equations have the following form for a no-conducting material with no free charges: [5]

$$\nabla \times E =^{-} \frac{\partial B}{\partial t} \tag{I.2}$$

$$\nabla \times H = \frac{\partial D}{\partial t} \tag{I.3}$$

$$\nabla . D = 0 \tag{I.4}$$

$$\nabla . B = 0 \tag{I.5}$$

Where **E** is the electric field vector, **H** is the magnetic field vector .and **D** and **B** are the corresponding flux densities. The constitutive relations establish a relationship between the flux densities and the field vectors.

$$D = \varepsilon_0 E + P \tag{I.6}$$

$$B = \mu_0 + M \tag{I.7}$$

Where ε_0 is the vacuum permittivity, μ_0 is the vacuum permeability. The induced magnetic and electric polarizations are denoted by P and M, respectively. M=0 for optical fibers due to silica glass's nonmagnetic property.

The relationship between P and E can generally be nonlinear. A discussion of fiber modes can overlook the nonlinear effects of optical fibers despite their significant interest. Next, the relationship links P and E together:

$$P(r,t) = \int_{-\infty\infty}^{\infty} x\,(r, t - t')E(r, t')dt' \tag{I.8}$$

Generally, linear susceptibility χ is a second-rank tensor; however, it decreases to a scalar in an isotropic medium like silica glass. Unintentional changes in the core shape cause optical fibers to become slightly birefringent.

Equation (1.8) incorporates the temporal response's delayed nature, a characteristic that significantly affects optical fiber communications due to chromatic dispersion.

Equations (1.2)-(1.8) provide a general framework for analyzing wave propagation in optical fibers. This makes using a single field variable E convenient in practice. Equations (1.3) - (1.6) and (1.7) generate the wave equation by calculating the rotation of Equation (1.2)

$$\nabla \times \nabla \times \mathrm{E} = -\frac{1}{\mathrm{c}^2}\frac{\partial^2 \mathrm{E}}{\partial \mathrm{t}^2} - \mu_0 \frac{\partial^2 \mathrm{P}}{\partial \mathrm{t}^2} \tag{I.9}$$

Where $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$ defines the speed of light in a vacuum as usual, by introducing the Fourier transform of *E(r, t)* through the relation:

$$\tilde{E}(r,\omega) = \int_{-\infty}^{\infty} E(r,t)\, exp(i\omega t)\, dt \tag{I.10}$$

As well as an equivalent connection for *P(r, t)*, thereby equation (1.8) can be utilized to write equation (1.9) in the frequency domain as:

$$\nabla \times \nabla \times \tilde{E} = -\varepsilon(r,\omega)\left(\frac{\omega^2}{c^2}\right)\tilde{E} \tag{I.11}$$

Where the expression of the frequency-dependent dielectric constant is:

$$\varepsilon(r,\omega) = 1 + \tilde{x}(r,\omega) \tag{I.12}$$

Where $\tilde{x}(r,\omega)$ is $x(r,t)$Fourier transform. $\varepsilon(r,\omega)$ is complex in general. The definition of its real and imaginary portions relates them to the refractive index n and the absorption coefficient α.

$$\varepsilon = (n + i\alpha c/2\omega)^2 \tag{I.13}$$

By using equation (1.13) and (1.14), n and α are related to $\tilde{\chi}$ as:

$$n = (1 + \mathrm{Re}\tilde{x})^{1/2} \tag{I.14}$$

$$\alpha = (\omega/nc)Im\tilde{x} \tag{I.15}$$

In this case, the real and imaginary components are denoted by the letters R_e and I_m. The frequency dependence of α and n is present. What is known as chromatic dispersion, or just material dispersion, is the frequency dependence of n. It has been demonstrated that fiber dispersion significantly reduces the performance of fiber-optic communication networks.

Two more simplifications can be performed before solving equation (1.11). First because silica fibers have negligible optical losses, ε can be assumed accurate and replaced by n_2. Second, one can use the identity since *n(r,ω)* in the core and cladding of a step-index fiber is independent of the spatial coordinate r.

$$\nabla \times \nabla \times \tilde{E} \equiv \nabla(\nabla \cdot \tilde{E}) - \nabla^2\tilde{E} = -\nabla^2\tilde{E} \tag{I.16}$$

Where we set $\nabla = 0$ using Equation(1.4) and the relation $D = \varepsilon E$. When the index changes across a length scale much longer than the wavelength, equation (1.16) then roughly holds. Applied to equation (1.11) via equation (1.16), we get:

$$\nabla^2\tilde{E} + n^2(\omega)k_0^2\tilde{E} = 0 \tag{I.17}$$

Where the free-space wave number k_0 is defined as:

$$\mathrm{k}_0 = \omega/\mathrm{c} = 2\pi/\lambda \tag{I.18}$$

And the vacuum wavelength of the optical field pulsating at frequency ω is represented by λ. The step-index fibers' optical modes are then obtained by solving equation (1.17). [23]

I.5.3 Impairments of the optical fiber channel

The performance of optical communication systems can be negatively impacted by a number of impairments that can influence optical fiber channels. There are susceptible to two main categories of impairments that degrade signal transmission:

I.5.3.1 Fiber linear effects

Linear impairments in optical fiber channels arise from physical properties of the fiber itself and cause signal distortion without introducing new frequencies. Here are some of the key ones:

I.5.3.1.1 Attenuation

The light pulse loses intensity as it passes through the fiber. Two processes lead to attenuation in optical fibers such as scattering and absorption.

The glass molecules in the fiber absorb light and transform it into heat, which causes absorption. Dopants and leftover OH-ions are the main absorbers that alter the glass's refractive index.

However, dispersion is the primary cause of attenuation when a particle and a wave interact so that the energy from the directed propagates. [24]

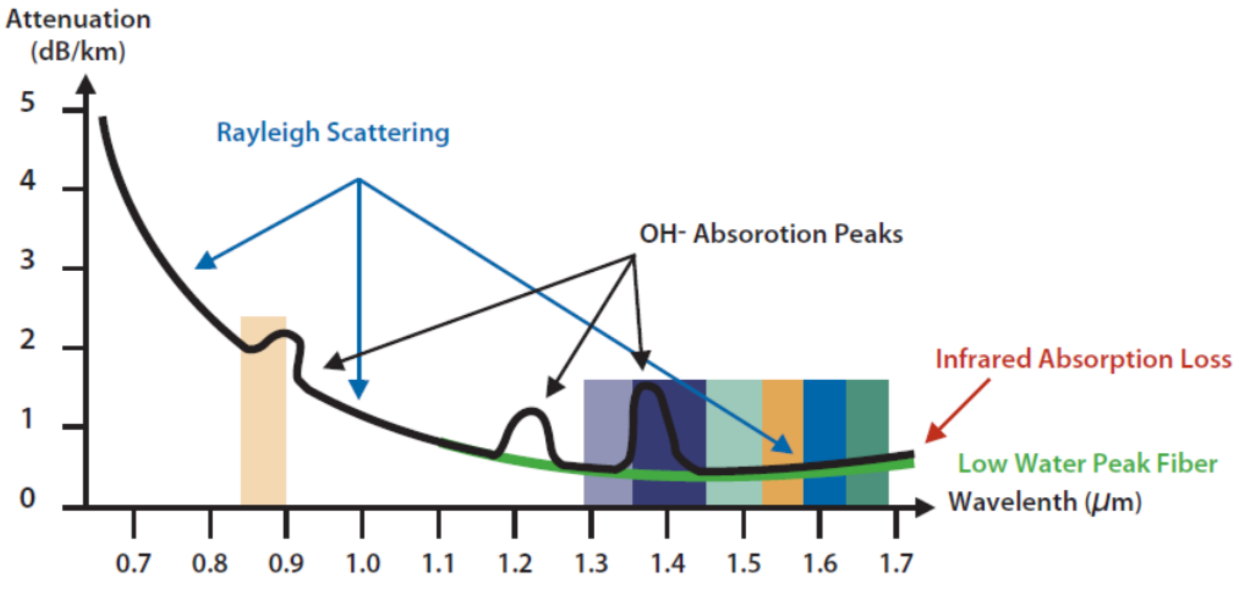


Figure I.13: *Attenuation rate of optical fiber as a function of the wavelength.* [25]

I.5.3.1.2 Chromatic dispersion

Laser sources are not monochromatic in fiber-optic transmission systems, even if their spectra are narrow. This suggests that the light pulse input contains many wavelength components. Spectrum broadening is also naturally induced by modulating the optical carrier.

The phenomenon known as chromatic dispersion occurs when various spectral components of a light pulse, depending on their frequency, have varying velocities (travel at different speeds) in the medium. Inter-symbol interference results from the pulse spreading as the slower wavelengths of one pulse interact with the faster wavelengths of the subsequent pulse.

Chromatic dispersion is caused by two factors: waveguide dispersion, which is connected to waveguide parameters, and material dispersion, which is related to the fiber material's refractive index dependence on wavelength.

As previously stated, chromatic dispersion causes a brief light pulse to propagate and become longer. Group velocity dispersion is the term for this phenomenon, which may be measured as the derivative of the reciprocal of the group velocity concerning the radian frequency. [24]

I.5.3.1.3 Polarization mode dispersion

In dual-polarization systems, the electrical field of the transmitted polarization-multiplexed signal can be divided into two orthogonal polarizations, each conveying a different signal. In an ideal optical fiber, the two orthogonal polarizations propagate at the same speed. However, in a realistic fiber, the two polarizations propagate at fractionally different velocities because of random flaws, non-circularity of the core, an accumulating phase shift, and a corresponding differential delay in proportion to distance (called birefringence). This phenomenon is known as polarization mode dispersion, or PMD for short. [24]

I.5.3.2 Fiber nonlinear effects

Another type of distortion a signal going via a fiber-optic channel may encounter is nonlinear impairments, which are more common in long-distance transmissions. The most common nonlinear effects in optical systems can be divided into two groups: the Kerr effect (caused by a nonlinear index of refraction), stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS). [11]

I.5.3.2.1 Kerr effects

The term "Kerr effect" refers to the change in a material's refractive index that occurs when an electric field is applied, this change is proportional to the square of the applied electric field rather than linear. [11]

The effective refractive index originates from this phenomenon, based on the inharmonic mobility of bound electrons under the influence of the applied electromagnetic field.

The refraction index, consisting of a linear part n_0(in the absence of an optical signal) and a nonlinear part n_2, which depends on the optical intensity in the fiber (Kerr effect), is expressed as follows [11]:

$$n = n_0 + n_2|E|^2 \quad (I.19)$$

I.5.3.2.2 Stimulated Raman scattering SRS

SRS is a nonlinear scattering effect that occurs in optical fibers, when the material's interaction with light causes the optical energy to flow from the pump wave to the Stokes wave. Energy moves from the pump wave to the Stokes wave in this inelastic process. SRS in optical fibers can happen both forward and backward. [26]

I.5.3.2.3 Erbium-doped fiber amplifiers (EDFA)

Periodic signal amplification is required to operate long-haul lightwave systems, such as traversing transoceanic distances, even with low-attenuation optical fibers. Due to the introduction of erbium-doped fiber amplifiers in the 1990s, amplification could be achieved without optical-electrical conversion; hence, optical long-haul systems relied on expensive electrical regeneration. Optical amplifiers available on the market generally operate in the transmission window at the wavelength of 1550 nm. [26]

Essential operation: the fundamental principle of all-optical amplifiers is the same. A pump wave stimulates the material, and stimulated emission coherently amplifies the incident light. An erbium-doped fiber amplifier (EDFA) is made of erbium ions (Er^{+3}); amplifiers with varying wavelengths can be constructed using additional rare earth elements, including holmium, neodymium, samarium, thulium, and ytterbium. [27]

Figure 1.14 illustrates that the outer shell electrons of an erbium ion occupy three energy levels (E1, E2, and E3). E1 is the ground state, E2 is the metastable state, and E3 is the high-energy state.

When simulating an erbium-doped fiber with a high-energy pump laser, many bound electrons of the erbium ion are simulated from the ground state to the high-energy state (E3).

Erbium ions decay radiationless (no photons are produced) and attain the metastable state E2 very quickly because the high-energy state is unstable.

A particle can persist in E2, a metastable energy state, for an extended period. In radiationless transition mode, the particles generated by the pump laser constantly come together to reach this state, resulting in the population inversion distribution.

Upon passing through the erbium-doped fiber in response to optical signals with a wavelength of 1550 nm, particles in the metastable state transition to the ground state in stimulated radiation mode, producing photons identical to those of the input signal. This increases the number of photons in the signal light, which causes the signals to rise as they continuously move through the erbium-doped fiber. [28]

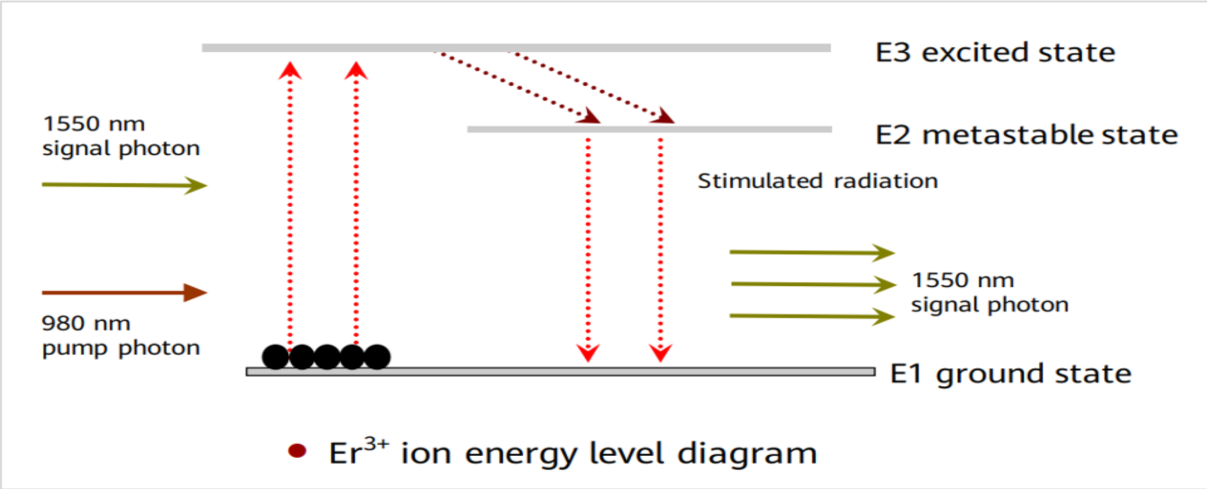


Figure I.14: *Energy levels of erbium ions.* [29]

I.6 Coherent receiver with digital signal processing

Coherent receivers in optical communication systems are combined with digital signal processing (DSP) [30] [31]. They usually consist of several functional components that carry out different crucial functions. The figure 1.15 below shows the block diagram of the coherent receiver.

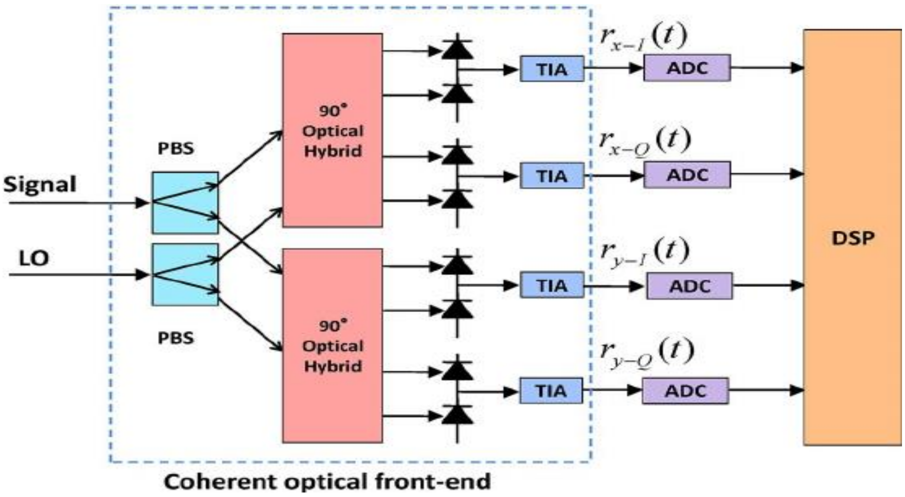


Figure I.15*: block diagram of the coherent receiver comprising phase and polarization diversities. LO: local oscillator, PBS: polarization-beam splitter, TIA: transimpedance amplifier, ADC: analog-to-digital converter, and DSP: digital signal-processing circuit.* [32]

Optical Front-End: This block uses a photodiode to convert optical signals to electrical signals after receiving the incoming optical signal.

Local Oscillator (LO): To create a baseband electrical signal, the incoming signal is combined with the local reference signal produced by this block.

Analog-to-Digital Converter (ADC): This device takes a block sample of the electrical signal in the baseband and transforms it into a digital signal.

Digital signal processing (DSP): This block handles several signal processing functions, such as equalization, polarization demultiplexing, chromatic dispersion compensation, and carrier phase recovery.

Error Correction: This block uses forward error correction (FEC) techniques to repair mistakes in the received signal.

Data Recovery: This block recovers the original data from the error-corrected signal.

One factor driving the recent resurgence of interest in coherence detection is the need for higher data rates, which necessitates the identification of spectrally effective modulation schemes. Coherent receivers provide full access to the optical field, enabling modulation of both quadrature.

However, electronic digital signal processing (DSP) developments have allowed for the construction of coherent receivers with comparatively little (optical) complexity. However, electronic digital signal processing (DSP) developments have allowed for the construction of coherent receivers with comparatively little (optical) complexity. [27]

I.6.1. Coherent detection

There are three distinct forms of coherent receivers: intradyne, heterodyne, and homodyne receivers. These receivers can be identified by their unique features and detection techniques. [33]

- ❖ Homodyne receiver creates a baseband electrical signal by combining the incoming signal with a local oscillator (LO) signal at the same frequency.

  Homodyne receivers are simpler to design but require a highly stable LO due to the sensitivity to phase noise. Additionally, they may suffer from impairments due to direct current (DC) components in the signal.
- ❖ Heterodyne receiver creates an intermediate frequency (IF) electrical signal using an LO signal slightly different from the incoming signal.

  Heterodyne receivers offer better tolerance for LO phase noise compared to homodyne systems. However, they require additional components for frequency conversion, increasing complexity.
- ❖ Intradyne receiver: if the signal's bandwidth exceeds the intermediate frequency, the process is called intradyne detection.

Intradyne receivers offer advantages like simpler design and reduced sensitivity to LO phase noise. However, they may be less efficient in terms of spectral usage compared to other types.

The choice of coherent receiver type depends on factors like system requirements, desired performance, complexity constraints, and cost considerations.

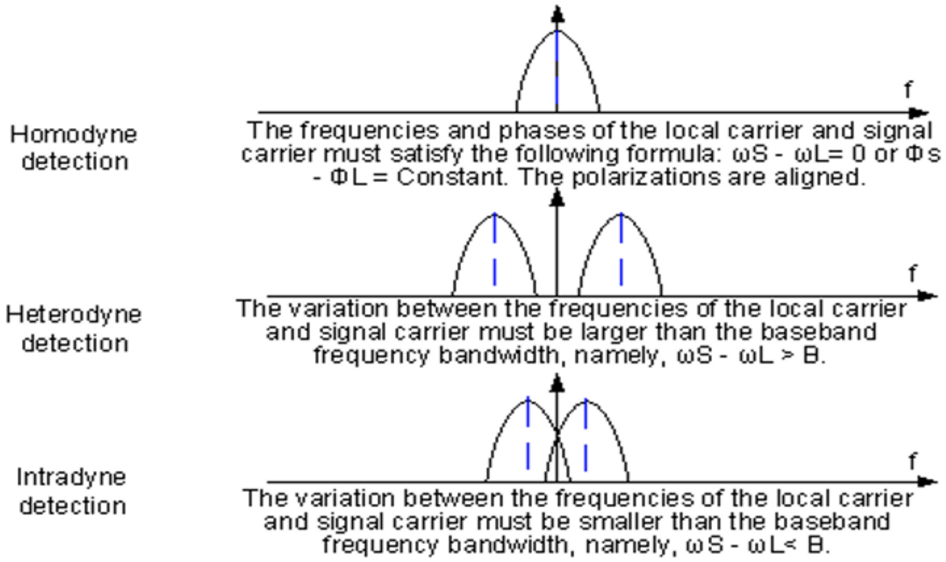


Figure I.16: *Forms of coherent detections.* [34]

I.6.2 digital signal processing blocks

A coherent receiver's digital signal processing (DSP) blocks carry out several crucial functions to extract polarization, amplitude, and phase information from the incoming optical signal. Depending on the implementation, the precise DSP blocks may change. However, the typical blocks are as follows [35]:

I.6.2.1 Symbol Clock Synchronization:

The symbol clock defines the timing intervals for each data symbol in the signal. Accurate symbol clock recovery is crucial for proper sampling and demodulation of the received data.

DSP block uses techniques like decision-directed algorithms to analyze the received signal and extract the symbol clock information. By aligning the receiver's sampling clock with the recovered symbol clock, the DSP ensures that each symbol is sampled at the correct time for accurate decoding.

I.6.2.2 Equalization and Polarization Demultiplexing:

- **Equalization (Compensation techniques):** The signal can be distorted by various factors during transmission. It essentially reshapes the received signal to recover the original pulse shape and minimize ISI. This DSP block uses equalization filters to compensate for these distortions and improve the signal quality.

- **Polarization Demultiplexing:** In coherent receivers, the signal often utilizes both polarizations of light (horizontal and vertical) to carry information. This block separates the information encoded on each polarization for separate processing and decoding.

I.6.2.3 Frequency and Carrier Phase Recovery:

During transmission, the phase of the received signal can fluctuate due to noise and other impairments. This phase noise can lead to symbol errors if not corrected. The carrier phase recovery block estimates and tracks the phase changes of the received signal. It then corrects for these changes by adjusting the phase of a reference signal within the DSP. This ensures accurate symbol decoding.

I.6.2.4 Error correction

This block uses forward error correction (FEC) algorithms to rectify mistakes in the received signal.

It works by adding redundant information (parity bits) to the original data stream before transmission. At the receiver, these parity bits are used to detect and, in some cases, correct errors in the received data. IFEC significantly improves the Bit Error Rate (BER) of the received data. This translates to more reliable data transmission, especially in noisy environments or long-haul communication systems. [36]

I.6.2.5 Data recovery

From the error-corrected signal, this block retrieves the original data. [36]

After error correction, the processed signal contains the recovered data symbols. The data recovery block performs the final step of extracting the original data from these symbols.

- **Mapping:** The data recovery block uses the modulation format information (e.g., QPSK, 16QAM) to map the received symbols back to their corresponding data bits. This mapping process essentially translates the encoded symbols into the original data stream.
- **De-interleaving:** In some systems, the data may be interleaved before transmission to improve its resilience to burst errors. The data recovery block performs de-interleaving to reverse this process and restore the original data order.

By performing these final steps, the DSP effectively recovers the original data from the received optical signal, ready for further processing or use.

I.7 system performance

Having precise and trustworthy techniques for evaluating the performance of optical networks has become crucial as optical communication technology develops. The Bit Error Rate (BER), Q Factor, and Optical Signal-to-Noise Ratio (OSNR) are the metrics that are most frequently used for this purpose.

I.7.1 The Bit Error Rate BER

The bit error rate (BER) is the ratio of the number of received bits containing errors to the total number of transmitted bits. It's essentially a measure of how many errors occur during data transmission over a communication channel. [37]

It's typically expressed as a decimal or a percentage. The formula is indicated as:

$$BER = \frac{Number\ of\ erroneous\ bits}{Total\ number\ of\ transmitted\ bits} \qquad (I.20)$$

In our simulations, the error rate assessment is based on the utilization of the Monte Carlo method. This approach estimates the error rate within a confidence interval with a predefined probability. The probability of errors can be calculated using mathematical expectation.

Depending on the desired accuracy of the measurement, a specific number of errors is considered. Then, the sum of these errors is divided by the number of bits examined during error counting $\mathbf{N_{MC}}$.

The number of errors can range from 100 to 500 depending on the desired level of precision in the estimation.

Therefore, a higher estimation quality is achieved when the number of errors N_{MC} is high. However, when error rates are low, using the Monte Carlo method can become time-consuming in terms of computational time. [37]

I.7.2 Q factor

The Quality Factor (Q Factor) is an indicator of the noise level of an impulse. It is defined as the ratio between the average optical signal power and the minimum average total noise power (SNR) required to obtain a specific binary error rate for a given signal.

There are various ways to compute Q Factor: the differential phase-shift key approach, the eye-diagram method, and others. It can be calculated mathematically using the equation below [37];

$$P_e = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}) \qquad (I.21)$$

I.7.3 Optical signal to noise ratio (OSNR)

In fiber optic communications, OSNR is an essential statistic that shows the quality of the signal after it has traveled over an optical network. Its definition is the signal-to-noise power ratio within a given bandwidth. System performance improves with greater OSNR values.
OSNR is calculated using the formula: [38]

$$OSNR(dB) = 10log\frac{P_{signal}(mW)}{P_{noise}(mW)} = P_{signal}(dBm) - P_{noise}(dBm) \quad (I.22)$$

I.7.4 OSNR penalty

OSNR penalty, also called crosstalk penalty, is the difference between the required OSNR for a given BER without any interfering signals and the required OSNR for the same BER with these interferers. It describes the reduction in the required OSNR caused by interfering signals, such as crosstalk. [39]

I.7.5 Transmission Reach (Transmission distance × capacity)

In coherent optical systems, transmission reach is the maximum distance that optical signals can be reliably transmitted without experiencing a significant increase in bit error rate (BER) or degradation in signal quality. A number of factors, including fiber loss dispersion and amplifier noise, can affect transmission reach. [40]

I.8 Conclusion

The objective of this chapter has been to offer a concise overview of fundamental principles in coherent optical communication systems. The subjects covered encompass transmitters, the fiber channel model, the architecture of a coherent receiver, and the conventional DSP blocks utilised in estimating the transmitted data. The discussion focused on the principal system performance to evaluate their efficiency.

Chapter II:

Digital back propagation technique for Nonlinearity compensation in coherent optical systems

II.1. Introduction

Research on digital back propagation for nonlinearity compensation in coherent optical systems is of the utmost importance. It plays a crucial role in reducing the detrimental impacts of nonlinearities in optical fiber transmission. The nonlinear effects caused by the interaction between light and the fiber medium can significantly degrade the quality of transmitted signals, limiting the performance of optical communication systems.

Nevertheless, the advent of digital back propagation techniques, which utilize signal processing algorithms at the receiver to effectively mitigate distortions caused by fiber nonlinearity, offers a promising solution for addressing these nonlinear impairments.

The research in this field concentrates on developing intricate algorithms and strategies to reduce the impact of nonlinear phenomena that occur when signals travel through optical fibers, including self-phase modulation, cross-phase modulation, and four-wave mixing.

The researchers want to enhance the overall performance of coherent optical systems by employing digital back propagation, increasing transmission distances, and enhancing signal quality. This technique mitigates the impact of nonlinearities effectively. It enables the creation of reliable and efficient optical communication networks with large data capacities.

In this chapter, we provide the fundamentals of the nonlinear effects in the optical fiber including its leading impacts of each effect, then the mathematical concept of the digital back propagation technique we are going to use for compensating the nonlinear effects.

II.2. Fundamentals of nonlinear effects in optical fiber

In optical fibers, nonlinear effects are a crucial aspect of understanding light propagation in optical fibers. Here's the two main origins of these nonlinearities as shown in the figure below:

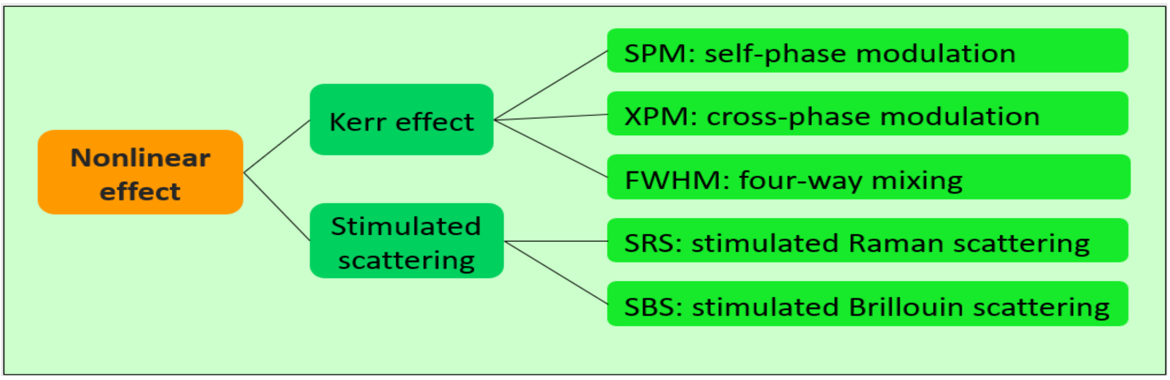


Figure II.1: *Nonlinear effects in optical systems*. [41]

II.2.1 Inelastic Scattering Phenomena

In some instances, high-intensity light waves can interact with the molecules within the fiber core. This interaction can cause the light to lose some energy, which is transferred to the molecules, exciting them to a higher vibrational state.

There are two main types of inelastic scattering phenomena relevant to optical fibers: Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) .[42]

II.2.2 Intensity Dependence of Refractive Index (Kerr Effect)

The term "Kerr effect" refers to the change in a material's refractive index that occurs when an electric field is applied, this change is proportional to the square of the applied electric field rather than linear.

The effective refractive index originates from this phenomenon, based on the inharmonic mobility of bound electrons under the influence of the applied electromagnetic field. [11]

II.2.3 Self-phase modulation (SPM) effect

This nonlinear effect, which causes a nonlinear phase shift and frequency chirping of optical pulses, is caused by the power dependence of the refractive index. SPM can increase signal bandwidth while significantly reducing lightwave system performance. While the effective mode area is inversely related to the nonlinear parameter γ, more significant mode areas can mitigate the effects of fiber nonlinearities. [43]

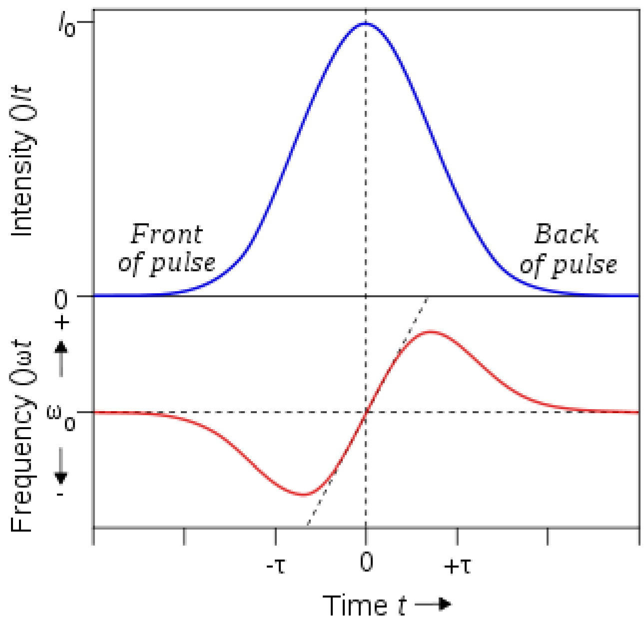


Figure II.2: *Self-phase modulation effect.* [44]

II.2.4 Cross-Phase Modulation (XPM) effect

This effect results from the interaction of several optical fields, which causes one wave's phase to be modulated by the intensity of another. Intensity variations can be transformed into phase noise by XPM, which affects coherent systems' performance. [43]

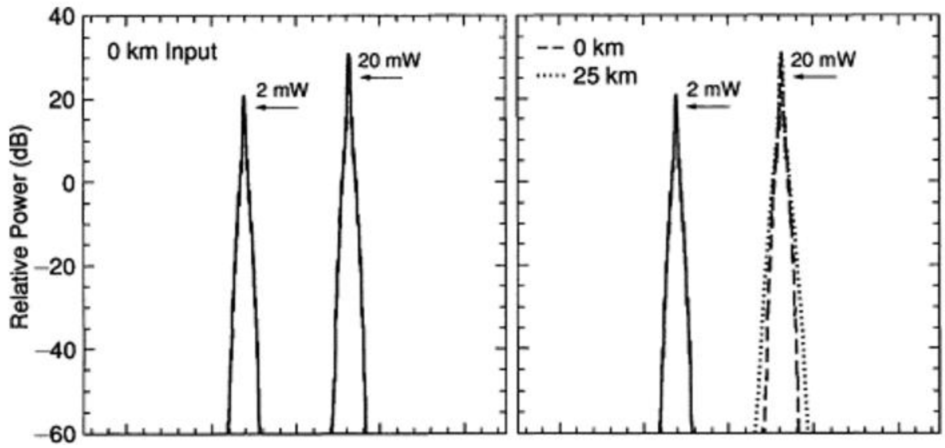


Figure II.3: *Cross-phase modulation effect.* [45]

II.2.5 Four Wave Mixing (FWM) effect

This nonlinear phenomenon results from the third-order nonlinear susceptibility. Four-wave mixing is a form of optical Kerr effect that happens when light with two or more distinct wavelengths is launched into a fiber, giving rise to a new wave (known as an idler) whose wavelength is not the same as any of the others. [46]

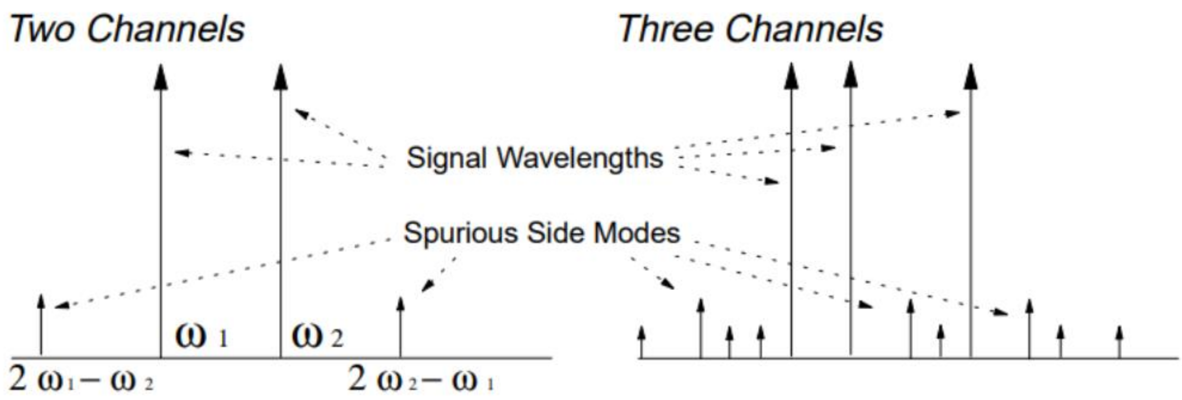


Figure II.4: *Four Wave Mixing effect.* [47]

II.3 Impact of the nonlinear effects on coherent optical systems

Nonlinear effects have a substantial impact on coherent optical communication systems, affecting many different elements of system performance. It can significantly impact the performance of coherent optical communication systems by introducing:

II.3.1 Nonlinear phase noise

In ideal conditions, the phase of a light wave in an optical fiber should remain constant during transmission. However, nonlinear effects like SPM and XPM cause the fiber’s refractive index to vary with the intensity of the signal. This variation in refractive index leads to fluctuations in the propagation speed of different parts of the signal's wavefront. Consequently, the phase relationship between different parts of the wavefront is no longer constant, resulting in phase noise. [48]

Phase noise cause errors in the interpretation of the digital data encoded on the optical signal. This leads to a higher Bit Error Rate (BER), impacting the overall reliability of data transmission.

II.3.2 Signal distortion

Nonlinear phenomena like Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) can distort the optical signal, resulting in extra noise and impairments that limit transmission distances and reduce signal quality. [48]

II.3.3 Bandwidth limitations

In coherent optical communication systems, multiple data channels are often transmitted simultaneously within a limited bandwidth.

FWM-induced spectral broadening can cause these channels to overlap, leading to inter-channel crosstalk. This crosstalk corrupts the information encoded on each channel, reducing the system's transmit data efficiently. The consequences of bandwidth limitations are [48]:

- Reduced System Capacity: Bandwidth limitations due to FWM restrict the number of data channels that can be transmitted simultaneously within the available bandwidth. This limits the system's overall data transmission capacity.
- Increased Signal-to-Noise Ratio (SNR) requirements: The crosstalk caused by FWM effectively adds noise to the signal. Higher SNR levels are required to maintain a good signal quality, which might necessitate reducing the transmission distance or increasing the signal power.

II.3.4 System Reliability

The nonlinear effects in coherent optical systems can lead to signal deterioration, power limitations, and impairments, diminishing reliability.
Understanding and effectively managing nonlinear effects are essential for maximizing the performance and reliability of coherent optical communication systems. Engineers can ensure reliable data transmission over long distances in modern optical communication networks by employing various design and management strategies. [48]

II.4 Optical nonlinearity compensation techniques:

Optical systems employ several compensation approaches to mitigate impairments and enhance overall system performance. One of these methods we are focusing on is:

II.4.1 Digital Back propagation (DBP) algorithm

The digital back propagation algorithm is crucial in coherent optical systems as it enhances signal transmission and effectively manages nonlinearities.
DBP is a computational technique implemented at the receiver in a coherent optical communication system. It aims to numerically "undo" the distortions caused by nonlinear effects experienced by the signal during its propagation through the optical fiber. [49]
DBP algorithm relies on DSP techniques to perform the complex calculations required for nonlinearity compensation. The DSP is generally implemented numerically by simplifying the inverse nonlinear Schrödinger equation (NLSE) with the split-step Fourier method (SSFM); the algorithm's performance is based on the calculation steps (h) to accurately estimate the transmission link parameters through transmission link design knowledge.

II.4.1.1 Non-linear Schrödinger equation (NLSE)

Maxwell's equations can be used to analyze how optical signals propagate in single-mode fibers (SMF). It can be expressed formally as a wave equation, e.g. in equation (2.1) [50]

$$\nabla^2 E = \frac{1}{c^2}\frac{\partial^2 E}{\partial^2 t} - \mu_0 \frac{\partial^2 P(E)}{\partial^2 t} \quad (2.1)$$

Where,

E: the electric field

$\boldsymbol{\mu_0}$**:** is the vacuum permeability

$\boldsymbol{c}$: is the speed of light

$\boldsymbol{P}$: is the polarization field.

Induced polarization has a linear relationship with the electric field at meager optical powers, such as:

$$P_L(r,t) = \varepsilon_0 \int_{-\infty}^{\infty} x^{(1)} (t - t`) \cdot E(r,t`)dt` \qquad \text{(II.2)}$$

Where ε_0 is the vacuum permittivity and $x^{(1)}$ is the first order susceptibility. To consider Non-linearities in the system, the equation (II.2) can be re-written as illustrated in equation (2.3):

$$P(r,t) = P_L(r,t) + P_{NL}(r,t) \qquad \text{(II.3)}$$

Whereas, $P_{NL}(r,t)$is the non-linear part of polarization. Equation (2.3) can be used to solve equation (2.1) to derive the propagation equation in nonlinear dispersive fibers with few simplifying assumptions.

First, P_{NL} is treated as a small perturbation of P_L and the polarization field is maintained throughout the whole propagation path. Another assumption is that the index.

The propagation constant, β(ω), is approximated by a few first terms of Taylor series expansion about the carrier frequency,ω_0, that can be given as;

$$\beta(\omega) = \beta_0 + (\omega - \omega_0)\beta 1 + \frac{1}{2}(\omega - \omega_0)^2\beta_2 + \frac{1}{6}(\omega - \omega_0)^3\beta_3 + \cdots \qquad \text{(II.4)}$$

Whereas;

$$\beta_n = \left[\frac{d^n \beta}{d\omega^n}\right]_{\omega=\omega_0} \qquad \text{(II.5)}$$

The dispersion effects in communication systems using optical fibers are taken into account by the second order propagation constant, β_2[ps^2/km]. The dispersion zone can be categorized as normal if ($\beta_2 > 0$) or anomalous if ($\beta_2 < 0$) depending on the sign of β_2.

D is the dispersion parameter and defined as $D = \frac{\mathrm{d}}{\mathrm{d}\lambda}\left[\frac{1}{v_g}\right]$. The mathematical relationship between β_2 and D is given as:

$$\beta_2 = \frac{\lambda^2}{2\pi c} D \qquad \text{(II.6)}$$

While the wavelength of the propagating wave is **λ**, and v_g is the group velocity. The cubic and higher-order terms in equation (2.4) are typically inconsequential. When the center wavelength of an optical signal is near the zero-dispersion wavelength, the terms β3 should be included for the signals' broad spectrum (that is, $\beta \approx 0$).

If the input electric field is assumed to propagate in the +z direction and is polarized in the x direction, equation (2.1) can be re-written as:

$$\frac{\partial}{\partial z}E(z,t) = \underbrace{-\frac{\alpha}{2}E(z,t)}_{linear\ attenuation} + \underbrace{j\frac{\beta_2}{2}\frac{\partial^2}{\partial^2 t}E(z,t)}_{second\ order\ dispersion} + \underbrace{\frac{\beta_3}{6}\frac{\partial^3}{\partial^3 t}E(z,t)}_{third\ order\ dispersion} - \underbrace{j\gamma|E(z,t)|^2E(z,t)}_{Kerr\ effect} \quad \text{(II.7)}$$

Where *E(z, t)* is the slowly changing envelope of the electric field, α is the loss coefficient [1/km], z is the propagation distance and β_2 is the second order propagation constant [ps^2/km],β_3 is the third order propagation constant [ps^3/km].

$\gamma = \frac{2\pi n_2}{\lambda_0 \, A\,eff}$ is the non-linear coefficient [km^{-1}. W^{-1}], n_2 is the nonlinear index coefficient, A_{eff} is the effective core area of the fiber, $\lambda_0$is the center wavelength and ω_0 is the central angular frequency.

When the pulse width is greater than 1ps, equation (2.7) can further be simplified because the Raman effects are negligible compared to the Kerr effect. Mathematically, the generalized form of the non-linear Schrödinger equation suited to signal transmission can be expressed as:

$$\frac{\partial E}{\partial z} = j\gamma|E|^2 + \left(-j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2} - \frac{\alpha}{2}\right)E = \left(\widehat{N} + \widehat{D}\right)E \quad \text{(II.8)}$$

Also, that D and N are termed as linear and non-linear operators as in equation (II.9).

$$\widehat{N} = j\gamma|E|^2; \widehat{D} = \left(-j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2} - \frac{\alpha}{2}\right) \quad \text{(II.9)}$$

As mentioned, the Nonlinear Schrödinger Equation (NLSE) accurately models signal propagation in fibers, considering both linear and nonlinear effects. [50]

II.4.1.2 Split-step Fourier method (SSFM) as NLSE Solution:

As mentioned, the Nonlinear Schrödinger Equation (NLSE) accurately models signal propagation in fibers, considering both linear and nonlinear effects. However, solving the NLSE can be computationally expensive for real-time applications. The most often used approach is the split-step Fourier method (SSFM), which well balances accuracy and computational efficiency. [50]

It breaks down the NLSE solution into smaller steps, where linear and nonlinear effects are treated separately.

The generalized version of the NLSE equation (2.8) includes two operators: The linear operator (D) represents the linear effects in the fiber, such as dispersion. The Nonlinear Operator (N) represents the nonlinear effects, such as Self-Phase Modulation and Cross-Phase Modulation.

The provided equation represents the analytical solution for propagating the electric field envelope (*E(z, t)*) from position z to z + h using SSFM.

$$E(z + h,t) = exp(h(\widehat{N} + \widehat{D})) \cdot E(z,t) \qquad \text{(II.10)}$$

h represents the step size, or propagation step length, through the fiber section. As in equation (2.11), it is expected that the two operators commute with one another in the split-step Fourier approach:

$$E(z + h,t) \approx exp\ exp\ (h(\widehat{N}\ ))exp\left(h\left(\widehat{D}\right)\right)E(z,t\ ) \qquad \text{(II.11)}$$

According to equation (II.11) it is possible to estimate *E(z + h, t)* by using the two operators separately. The results can be pretty accurate if is modest. Typically, the value of h is selected so that the non-linear operator's maximum phase shift value($\emptyset_{\max} = \gamma|Ep^2|h$, Ep is peak of $E(z,t)$ is less than a given value. The split-step Fourier approach simulates most optical communication systems well when φ_{max} is less than 0.05 rad.

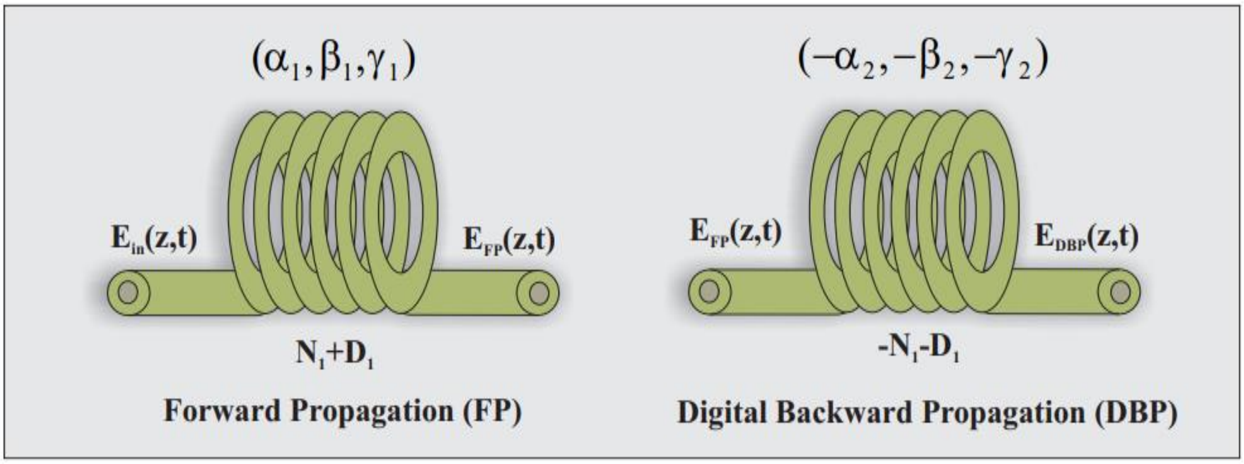


Figure II.5: *Block diagram of forward propagation (FP) and digital back propagation (DBP).* [51]

The distorted received signal can be used to determine the undistorted broadcast signal by solving the nonlinear Schrödinger equation inversely. After transmission, or forward propagation (FP), the received signal at the receiver is processed using a numerical model that combines the propagation parameters dispersion D and the non-linear coefficient γ with the negative sign.

Figure 2.5 shows the technique, which is known as digital back propagation (DBP). The non-linear Schrödinger equation with mathematical inverse can be expressed as (2.12):

$$\frac{\partial E}{\partial z} = (-\widehat{N} - \widehat{D})E \qquad \text{(II.12)}$$

Estimating the propagation parameters of the NLSE is the primary determinant of the DBP algorithm's performance. As was covered in the preceding section, the split-step Fourier method (SSFM) is utilized to solve NLSE with great numerical precision. Applying this DBP model to both the transmitter and receiver sides is possible. The DBP transmitter side is used when the signal is numerically distorted at the transmitter by the DBP algorithm. Then, this pre-distorted signal is broadcast across the fiber connection. Although DBP is typically done in conjunction with a coherent receiver, it is called receiver-side DBP. SSFM can be implemented by using two conventional methods:

II.4.1.2.1 Asymmetric SSFM (A-SSFM)

The asymmetric Split-Step Fourier Method (A-SSFM) is another variant of the SSFM used in Digital Back propagation (DBP) to compensate for nonlinear effects in optical communication systems. It applies the linear operator (L) followed by the nonlinear operator (N) within each propagation step (h), as illustrated in equation (2.13). [50]

$$E(z+h,t) = exp\left(h\hat{D}\right)exp\left(h\hat{N}\right).E(z,t) \qquad \text{(II .13)}$$

While a-SSFM simplifies calculations by not splitting the linear operator, it's important to note that this simplification comes at the cost of reduced accuracy compared to SSFM and S-SSFM, especially for long distances or strong nonlinearities.

A-SSFM might be suitable for shorter transmission distances or scenarios where computational efficiency is a primary concern, and high accuracy is optional. In certain situations, it can serve as a good balance between accuracy and complexity.

II.4.1.2.2 Symmetric SSFM (S-SSFM) method

Symmetric Split-Step Fourier Method approach aims to address these accuracy limitations by splitting the linear operator (L) into two halves and applying them around the nonlinear operator (N) within each step:

$$E(z+h,t) = exp\left(\frac{h\hat{D}}{2}\right) exp\left(h\hat{N}\right)exp\left(\frac{h\hat{D}}{2}\right).E(z,t) \qquad \text{(II.14)}$$

S-SSFM offers a significant improvement in accuracy compared to the standard SSFM, particularly for long-haul systems or scenarios with strong nonlinearities. S-SSFM significantly improves accuracy compared to the standard SSFM, particularly for long-haul systems or scenarios with strong nonlinearities.

While more accurate, S-SSFM involves slightly higher computational complexity than standard SSFM due to the additional linear operator evaluation. [50].

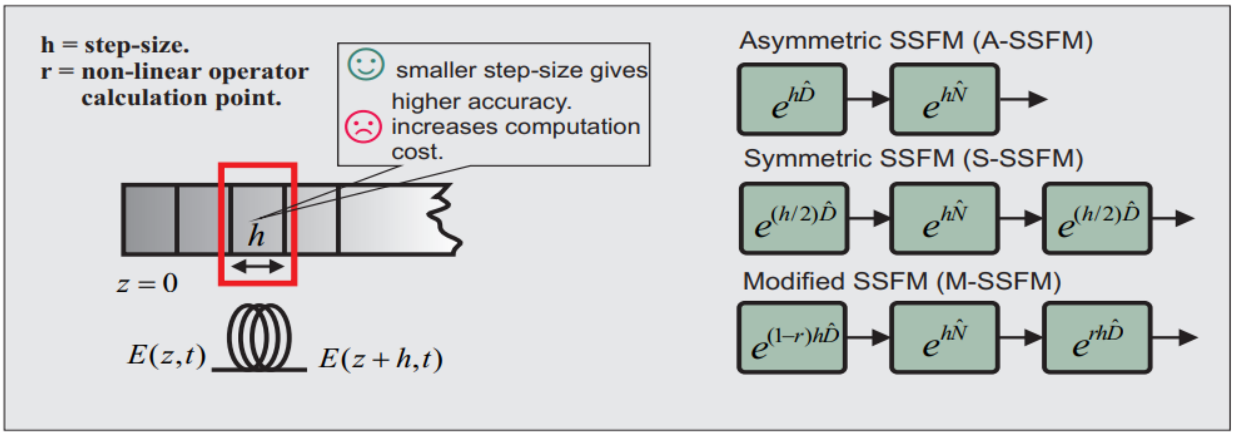


***Figure II.6:** Comparison of the split step Fourier methods.* [51]

The choice between SSFM, S-SSFM, and A-SSFM depends on the specific requirements of the communication system. Factors like transmission distance, desired accuracy, and computational resources must be considered. SSFM or S-SSFM are preferred for most practical applications due to their better accuracy.

II.5 Conclusion:

This chapter provides an extensive review of the basic nonlinear phenomena in optical fibers, including FWM, XPM, and SPM, along with their negative implications on system performance.

The nonlinear Schrödinger equation (NLSE) can be used to model nonlinear impairment mathematically. The split-step Fourier technique (SSFM) can be used to solve the equation, and digital back propagation (DBP) can be used to reduce these impairments.

To sum up, nonlinear effects represent a fundamental barrier to coherent optical fiber communications with high capacity. Although digital back propagation offers a useful way to make up for these deficiencies, its computational complexity still presents a problem. Advanced nonlinearity compensation methods, such as DBP, will become more and more critical as optical systems continue to push the envelope of capacity.

Chapter III:

Simulation of Digital-Back propagation for Mitigating Nonlinearity in Optical Communication Systems

III.1. Introduction

The Kerr nonlinearity imposes a constraint on the maximum achievable throughput of a single optical channel following transmission across a fiber channel. It does so by generating power-dependent distortions that restrict the signal-to-noise ratio (SNR) at the receiver. Fortunately, most of the distortions are predictable, and understanding the optical field at the receiver makes it possible to counterbalance their impacts. Nevertheless, the relationship between ASE noise and nonlinearities is a random process because of ASE noise's inherent nature. The mitigation of these effects is still an unresolved research topic.

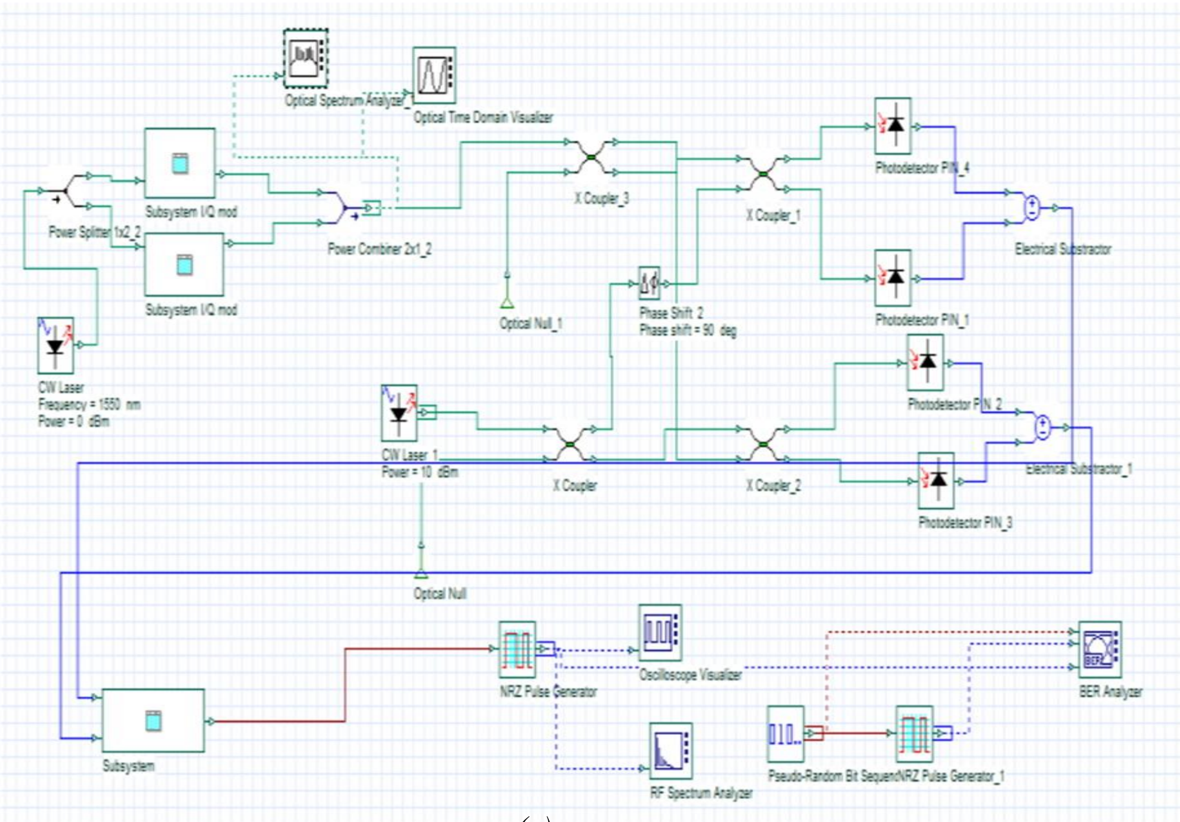
In this section, the numerical model considered for analysis is detailed. The numerical results obtained are discussed. In particular, we evaluate the influence of the symbol on the gains achieved by the studied algorithm by comparing different transmission configurations.

III.2. PDM-QPSK coherent optical system simulation

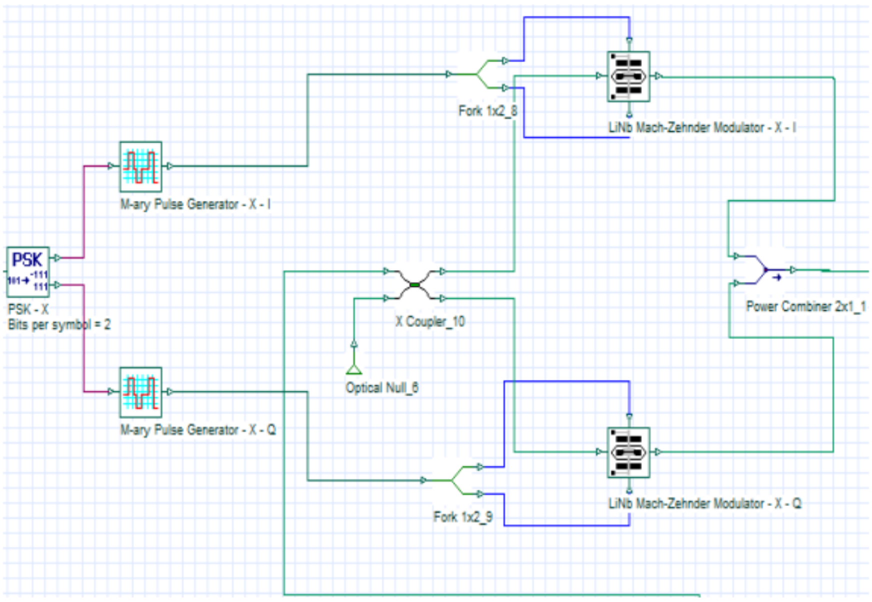
The numerical model for the considerate optical system is implemented and analyzed using MATLAB® software.

MATLAB® (MATrix LABoratory) software serves as a versatile platform for simulating optical systems. Its robust numerical computation capabilities and comprehensive libraries for mathematical functions make it well-suited for modeling the complex light propagation phenomena within optical systems. Furthermore, MATLAB offers powerful tools for data analysis and visualization, enabling researchers to effectively evaluate and interpret the simulation results. This facilitates the design, optimization, and performance prediction of various optical components and systems.

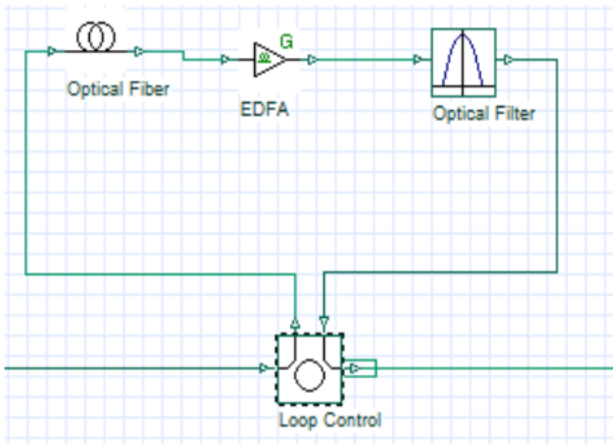
We carry out numerical simulations for a coherent PDM-0.3RZ-QPSK optical system using the technique of digital back propagation compensation in the electrical domain to validate the tolerability of digital compensation filters for nonlinear impairment. We used the numerical simulation model in Figure 3.1(a) to investigate the performance of single-channel DBP for various symbol rates.


Optical Spectrum Analyzer_1
Optical Time Domain Visualizer
Subsystem I/Q mod
Power Splitter 1x2_2
Subsystem I/Q mod
Power Combiner 2x1_2
X Coupler_3
X Coupler_1
Photodetector PIN_4
Electrical Substractor
Photodetector PIN_1
Optical Null_1
Phase Shift_2
Phase shift = 90 deg
CW Laser
Frequency = 1550 nm
Power = 0 dBm
CW Laser_1
Power = 10 dBm
Photodetector PIN_2
Electrical Substractor_1
X Coupler
X Coupler_2
Photodetector PIN_3
Optical Null
NRZ Pulse Generator
Oscilloscope Visualizer
BER Analyzer
Subsystem
RF Spectrum Analyzer
Pseudo-Random Bit Sequen
NRZ Pulse Generator_1

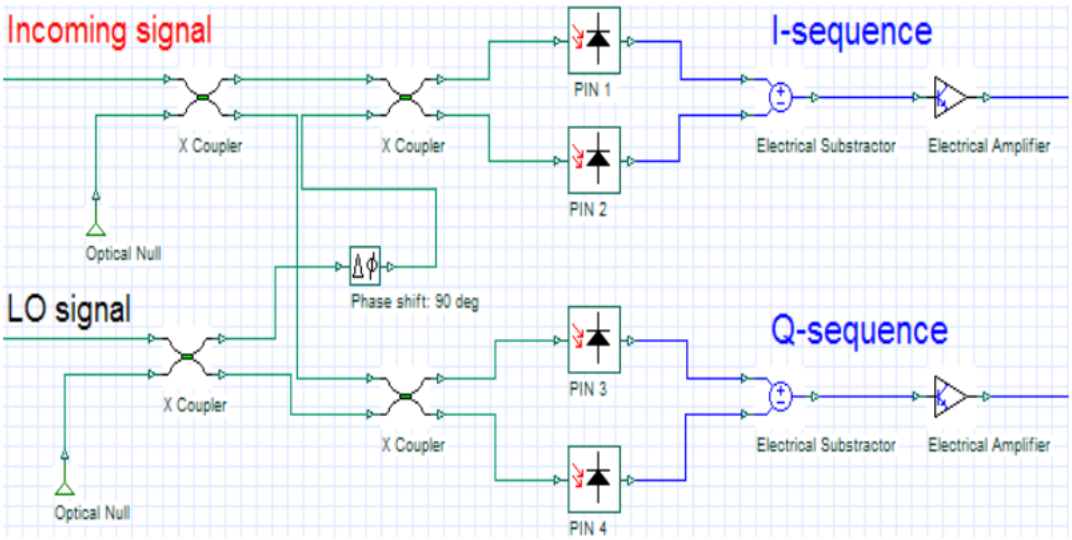
(a)


Fork 1x2_8
LiNb Mach-Zehnder Modulator - X - I
M-ary Pulse Generator - X - I
PSK
PSK - X
Bits per symbol = 2
X Coupler_10
Power Combiner 2x1_1
Optical Null_6
M-ary Pulse Generator - X - Q
LiNb Mach-Zehnder Modulator - X - Q
Fork 1x2_9

(b)



(c)



(d)

***Figure III.1**: (a) Block diagram of PDM-0.3RZ-QPSK coherent optical system, (b) QPSK Modulator, (c) optical link, (d) coherent detection.*

In this concept, a Pseudo Random Bit Sequence (PRBS) generator with a length of N_{bit} is used to modulate two orthogonally polarized QPSK optical signals. This modulation is achieved by employing two QPSK modulators. Figure 3.1 (b) depicts a QPSK Modulator that utilises a PSK Sequence Generator to produce two parallel M-ary symbol sequences from binary signals using phase shift keying modulation (PSK) (with 2 bits per symbol).

Subsequently, it traverses through the M-ary Pulse Generator to produce multilayer pulses based on the M-ary signal input, with a duty cycle of 0.3 bit. A laser emitting light with a wavelength of 1550 nm is divided into two separate parts. Each portion is then individually sent to Mach-Zehnder modulators. These modulators use Lithium Niobate to modulate the electrical signals.

Finally, the modulated signals from both MZMs are combined to form the final PDM-0.3RZ-QPSK optical signal. The simulation's parameters match those found in Table 3.1.

Table III.1: *The simulation parameters of a PDM-0.3RZ-QPSK transmitter.*

Parameters	**Values**
Bit rates R_{bit}	56-112-224 Gbps
Symbol rates R_{sym}	14-28-56 Gbaud
N_{bit}	4096
Sample/bit	64
number of sample	262144
Wavelength (λ)	1550 nm

The optical fiber models the transmission of an optical field in a single-mode fiber, considering both dispersive and nonlinear effects. This is achieved by numerically integrating the Nonlinear Schrödinger (NLS) equation for the scalar case. For our system when the polarisation state of the signal is arbitrary (dual polarisation), coupled NLS equations is used.

We implemented the transmission link in accordance with the explanation in Section 1.4 The transmitted signal is sent through an optical link made from the boucle of a monomode fiber (SSMF) that has been amplified by EDFA. In each span, the amplifier completely eliminates the accumulated fiber loss. There is no online optical compensation for the chromatic dispersion used. The polarization mode dispersion (PMD) effects were disregarded.

The optical fiber component simulates how an optical field moves through a single-mode fiber, taking into account both linear and nonlinear effects. This is achieved by numerically integrating the coupled nonlinear Schrödinger (NLS) equation for dual polarization case.

Using the symmetric split-step Fourier technique (SSFM) to solve the CNLSE equation numerically, the optical field propagation within the fiber was simulated, as explained in Section 2.4

The main factor causing deterioration in the transmission link, disregarding other influences, is the impact of intra-canal SPM (self-phase modulation). Table 3.2 provides a concise summary of the attributes of the optical liaison.

Table III.2: *The parameters of optical link.*

SSMF	**Parameters**
SSMF length	75 km
Attenuation	0.2 dB/km
Chromatic dispersion CD	16 ps/ (nm·km)
Wave length (λ)	1550 nm
Nonlinear refractive index (n_2)	2.7×10^{-20} (m^2/W)
Nonlinear parameter (γ)	1.3 (W.km)
Effective area (A_{eff})	80 μm^2
Gain	16 dB
Noise figure	5.5 dB

At the receiver end, the optical signals and the laser from the local oscillator (LO) are combined and accurately detected using a 4×90° optical hybrid (Homodyne detection). The transmitter and receiver lasers have the same linewidth of 100 kHz.

The four balanced photodiodes convert the phase and quadrature signals into four electrical signals. The noise of the photodiodes is ignored in all of the manuscript's results.

The incoming signals undergo processing using a Bessel low-pass filter of 5^{th} order. The filter has a 3dB bandwidth of 0.75 times the symbol rate (R_{sym}), and its purpose is to remove interference. Furthermore, analogue-digital converters synchronise incoming signals at a rate of 2 samples per symbol (Sa/Sym). The sample rate is equal to twice the value of R_{sym}. The captured signals are analyzed using digital signal processing (DSP) units to reduce distortions and recover the data. Finally, the decoded symbols are demapped in the binary form.

For nonlinearity compensation, DBP was performed with a fixed step size of z = 20 km (4 steps/span).

Therefore, to measure the bit error rate values presented in this work, the Monte Carlo method estimates an average of around 400 errors, this rate is subsequently converted into a quality factor Q using the following equation:

$$Q = 20log_{20}[\sqrt{2erfc^{-1}}(2BER) \quad \text{(III.1)}$$

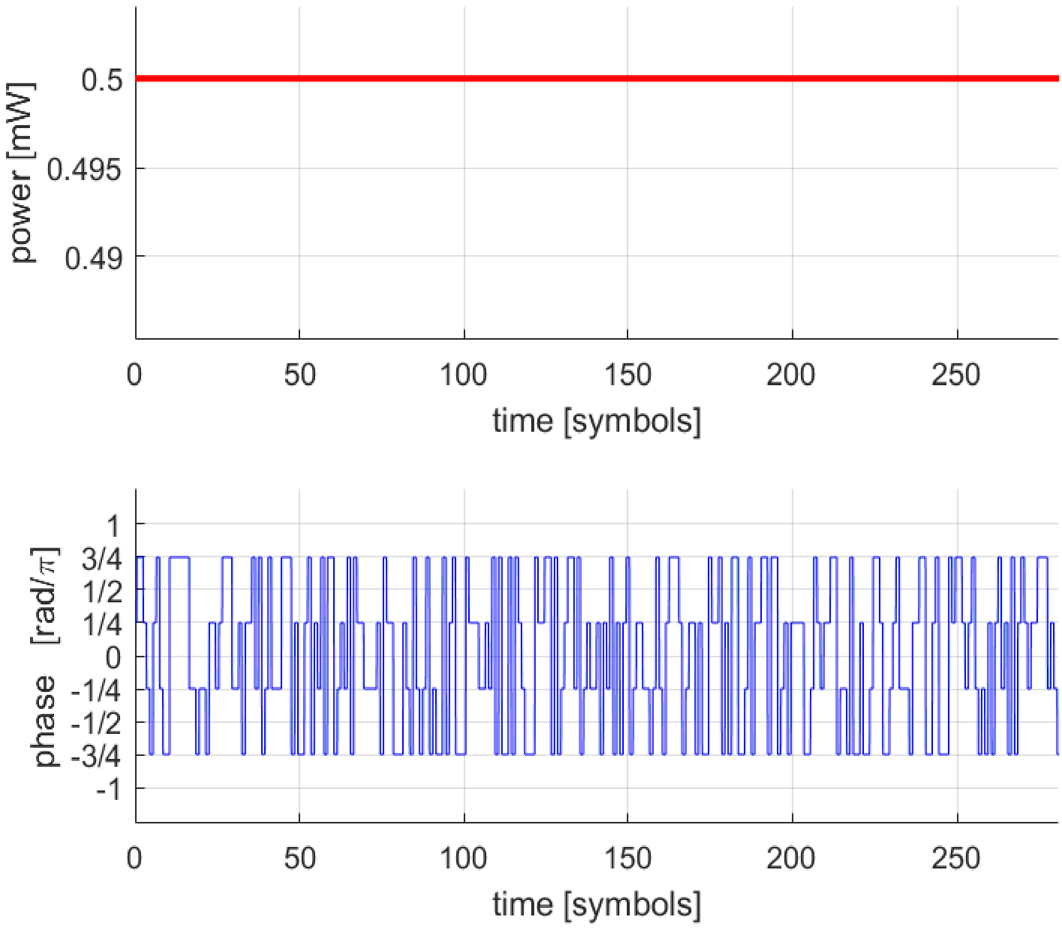
Where "erfc" is the error function.

III.3. Simulation results and discussion

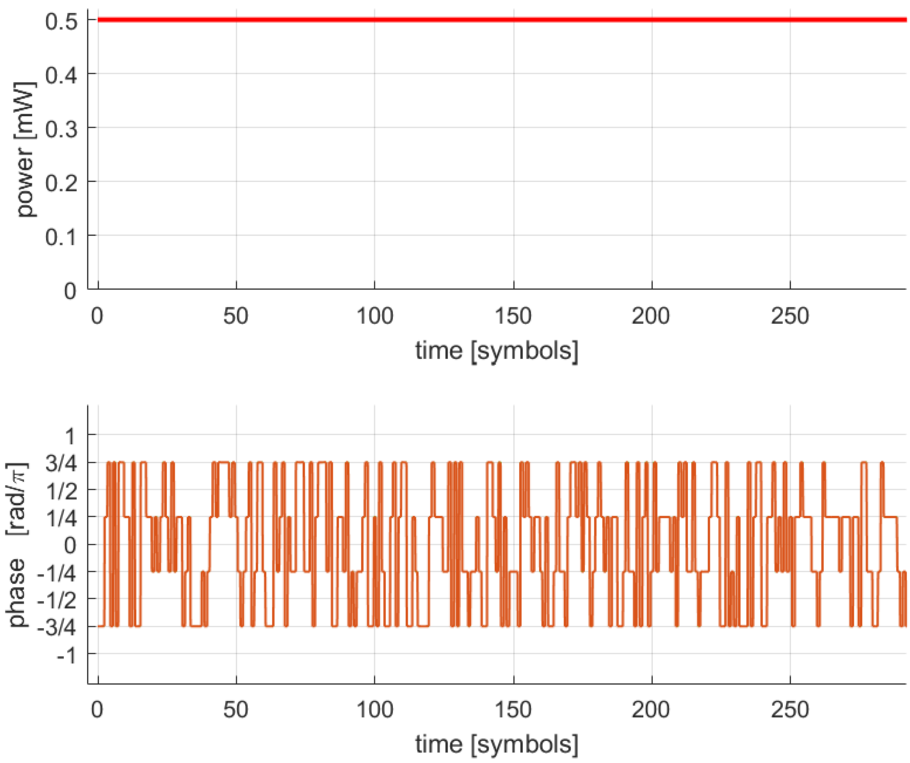
This section presents the results of the digital simulations as the signal propagates. We study the performance of the DBP compensation and evaluate the transmission characteristics of the PDM-0.3RZ-QPSK system in various configurations.

The nonlinear coefficient and the number of steps per section in the DBP module are always the same as those in the transmission fiber to ensure optimal operation of the DBP algorithm.

Figures 3.2 (a) and (b) show the amplitude and phase evolution of the optical signal PDM-0.3RZ-QPSK before and after the optical link. The optical signal's constant modulus and four-phase levels (π/4, −π/4, 3π/4, −3π/4) are observed. Moreover, Figure 3.3 shows the optical power spectrum of the transmitted QPSK signals.



(a)



(b)

Figure III.2: *The optical signal, (a) at output of transmitter, (b) through optical link.*

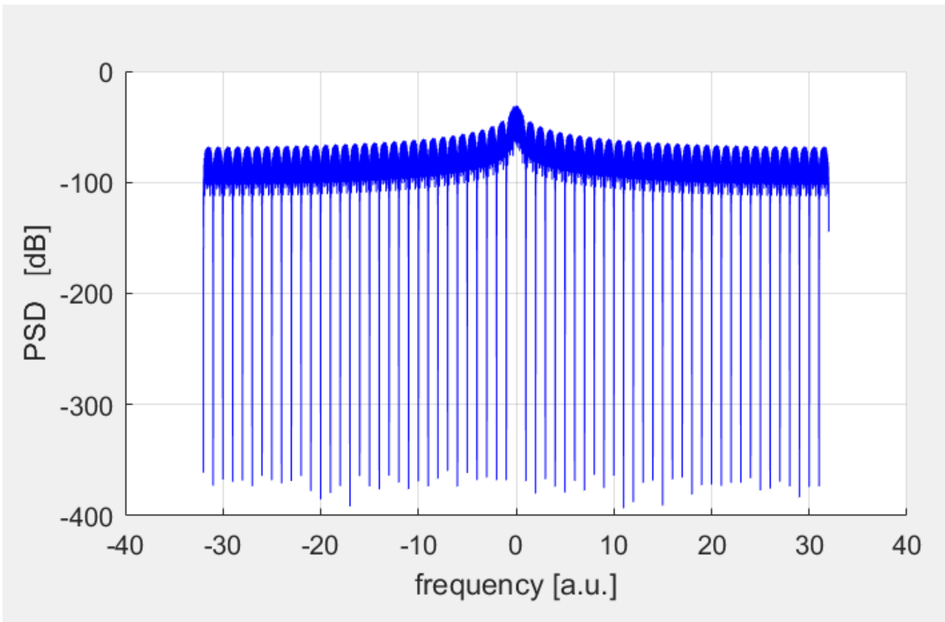
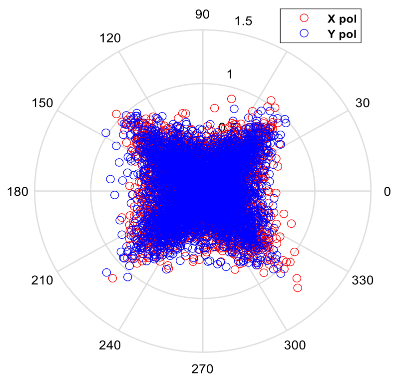


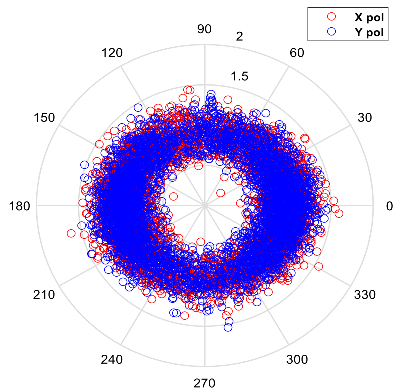
Figure III.3: *The optical power spectrum of QPSK signal.*

Figure 3.4 illustrates the receiver's output signals for X and Y polarizations in a constellation diagram. The constellation diagram for QPSK typically depicts a complex plane, with the X-axis representing the in-phase component and the Y-axis representing the quadrature component.

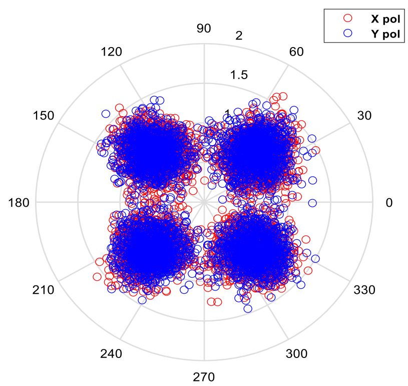
The constellation diagram reveals a distorted signal at the receiver input (case a). After applying the CMA algorithm, the constellation converges to a more circular shape (case b), indicating improved symbol separation and reduced inter-symbol interference. The four constellation points for the QPSK signal are located on a circle with equal spacing between them (case c), indicating the four symbols of QPSK modulation [00, 01, 10, and 11]. A normalized value of 1 typically represents the same amplitude for all four points. This indicates an equal power distribution among the different symbols. The phase angles of the points used to encode the data bits have different symbols.



(a)



(b)



(c)

Figure III.4: *Constellations of recovered signals in X-Y polarization,(a) input receiver, (b) after CMA,(c) after CPE .*

III.3.1. Nonlinearity compensation performance

III.3.1.1. Back-to-back configuration

In Figure 3.5, back-to-back performance (btb) of the PDM-0.3RZ-QPSK system is presented through the bit error rate versus OSNR (Optical Signal-to-Noise Ratio) for different symbol rates (14 Gbaud, 28 Gbaud, 56 Gbaud) at a resolution of 0.1 nm.

This refers to a measurement setup where the transmitter and receiver are directly connected with minimal impairments. The btb performance serves as a reference for the overall system performance without any transmission impairments.

For the three given symbol rates, the BER decreases as OSNR increases. This is because a stronger signal (higher OSNR) leads to fewer errors in the received data.

The curve for the lower symbol rate (14 Gbaud) has a steeper slope, indicating that the BER drops faster as OSNR increases compared to higher symbol rates. However, the curves might flatten out at higher symbol rates (28 Gbaud and 56 Gbaud) or even show a slight increase in BER at higher OSNRs due to increased complexity and susceptibility to impairments. The back-to-back BER of 14 Gbaud was less than 10^{-5} (corresponding to a Q-factor higher than 12.6 dB). The required OSNRs at the BER of 3.8×10^{-3} are 12.3 dB and 13 dB for 28 Gbaud and 56 Gbaud.

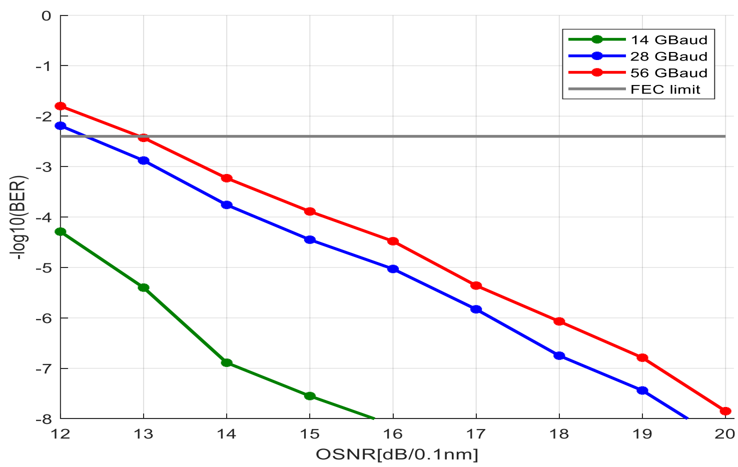
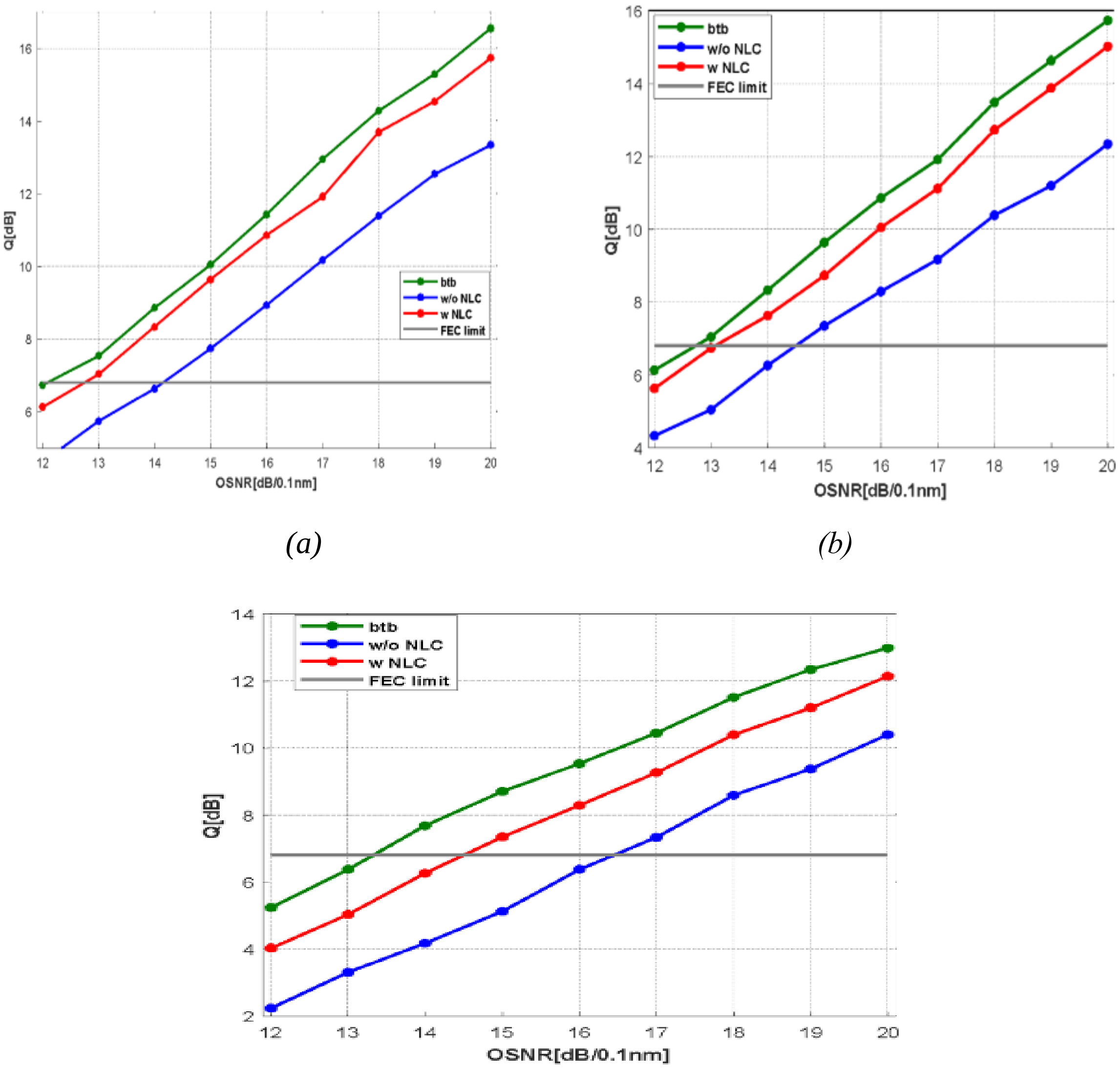


Figure III.5: *The measured receiver sensitivity curve (BER versus OSNR) for three symbols rates.*

III.3.1.2. Transmission configuration

We investigated the performance of NL compensation. In that case, the block of the backpropagation (BP) algorithm was implemented, using N_{steps} per span. A DBP algorithm based on the inversion of the Manakov equations was used. The nonlinearity compensation efficiency at the PDM-0.3RZ-QPSK optical system is studied, which is distorted by the intra-channel nonlinear effect (SPM) through a single-channel transmission.

The Q-factor as a function of the optical signal to noise ratio is measured to characterize the NLC performance of the PDM-0.3RZ-QPSK optical system under various scenarios, including back-to-back, without (w/o NLC) nonlinearity compensation, and with nonlinearity compensation (W NLC). We conducted this simulation for various symbol rates ranging from 14 to 56 GBaud, assuming a launched power (Pin) of 0 dBm and a transmission distance of 2450 km, as illustrated in Figure 3.6 (a)–(b)–(c).



(a) *(b)*

(c)

Figure III.6: *Q-factor versus optical signal-to-noise ratio for PDM-0.3RZ-QPSK System under different transmission scenarios, (a) 14 Gbaud, (b) 28 Gbaud, (c) 56 Gbaud.*

By comparing the results, it can be shown that as the symbol rates increases, the OSNR value also increases. The required OSNRs at a binary error rate of 3.8×10^{-3} (FEC threshold) are obtained in Table 3.3.

***Table III.3:** OSNR required values at the limit of FEC (Q of 6.8).*

Configuration	14 Gbaud	28 Gbaud	56 Gbaud
Btb transmission	12 dB	12.8 dB	13.3 dB
w NLC compensation	12.8 dB	13 dB	14.5 dB
w/o NLC compensation	14 dB	14.6 dB	16.5 dB

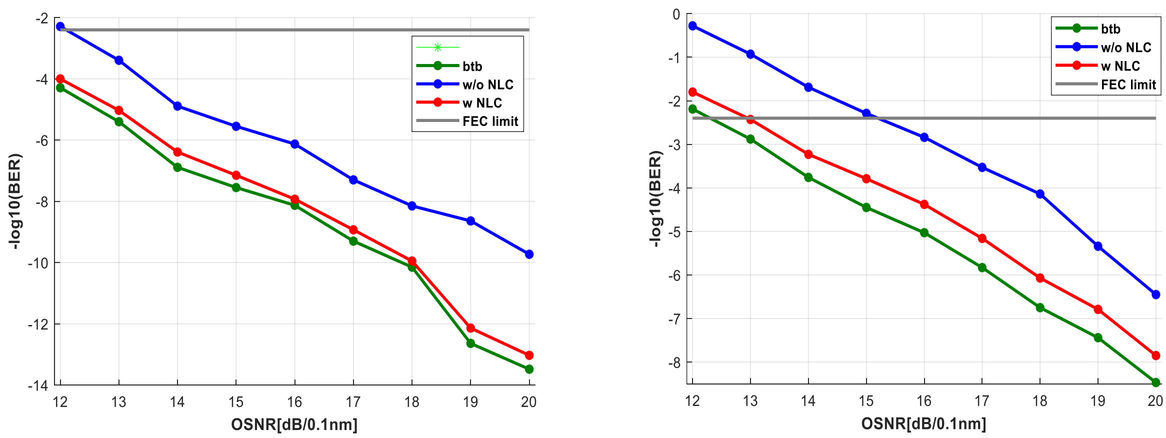
With forward error correction coding, the FEC limit line represents the minimum Q factor required to achieve a specific bit error rate threshold.

In case of transmission without using NL compensation, the symbol rates 14 Gbaud, 28 Gbaud experience lower OSNR penalties of 2 dB and 2.2 dB, respectively. On the other hand, at higher Baud rate (56 Gbaud), the penalty significantly increases to 3.2 dB. This is likely because higher symbol rates lead to more complex signals and greater susceptibility to inter-channel effects within the fiber optic channel, worsening signal quality.

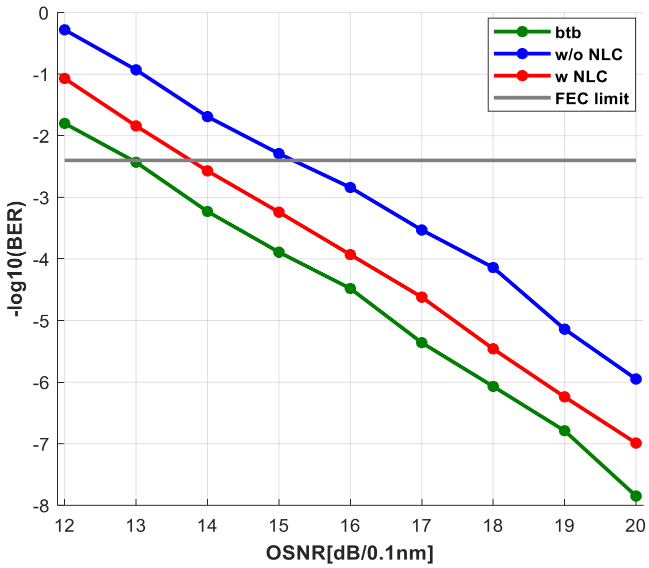
Applying the DBP algorithm seems to effectively mitigate the SPM effect. This results in a reduction in OSNR penalty:

- 1.2 dB improvement for 14 Gbaud.
- 2 dB improvement for both 28 Gbaud and 56 Gbaud.

Figures 3.7 (a)-(b)-(c) below show the BER performance versus the optical signal-to-noise ratio of the PDM-0.3RZ-QPSK system under the previously mentioned varied transmission situations for various bit rates (56-112-228) Gbps. The required OSNR values is presented in Table 3.4.



(a) *(b)*



(c)

Figure III.7: *BER versus OSNR for PDM-0.3RZ-QPSK System under different transmission scenarios, (a) 14 Gbaud, (b) 28 Gbaud, (c) 56 Gbaud.*

Table III.4: *OSNR required values at the limit of FEC (BER of 3.8×10^{-3}).*

Configuration	**14 Gbaud**	**28 Gbaud**	**56 Gbaud**
Btb transmission	Above FEC limit	12.3 dB	13 dB
w NLC compensation		13 dB	13.8 dB
w/o NLC compensation	12 dB	15.2 dB	16.6 dB

As expected, BER decreases with increasing OSNR for all symbol rates (14 Gbaud, 28 Gbaud, and 56 Gbaud). In both 14 and 28 Gbaud cases, the "back-to-back" (btb) scenario with no transmission distance has the lowest BER. For a given OSNR, the "without NLC" (w/o NLC) scenario has the highest BER, likely due to the accumulated SPM effect. This is because a higher OSNR signifies a stronger optical Kerr effect, leading to errors in the received data. The "with NLC" case has a slightly higher BER than the btb case, demonstrating NLC's effectiveness in mitigating NL effects and improving BER performance.

III.3.1.3 Maximum reach simulation results

We calculate the optimal injected power for the three different symbol rates in the 14–18–56 GBaud single-channel PDM-0.3RZ-QPSK system using a compensated SSMF fiber in the presence of the nonlinear SPM effect.

The system reach is plot as a function of the fiber launch power per channel. Figure 3.8 displays the simulation results using DBP (1 step per span case) for BER values of 3.8×10^{-3}. Transmission is linear at low power, so a doubling of power permits a doubling of reach. However, as the power increases further, the system experiences the NL transmission regime, resulting in curves that initially reach a maximum before descending.

The greatest reach of single-channel transmission is reduced when the Baud rate is increased: 4400 km may be reached at 14 GBaud, while only 4000 and 3750 km can be reached at 28 and 56 GBaud, respectively. The fact that the necessary higher baud rates generate more intrachannel NL effects (SPM) readily explains this. The optimum powers for 14 Gbaud, 28 Gbaud, and 56Gbaud are 0 dBm, 2 dBm, and 4 dBm, respectively.

As expected, BER decreases with increasing OSNR for all symbol rates (14 Gbaud, 28 Gbaud, and 56 Gbaud). In both 14 and 28 Gbaud cases, the "back-to-back" (btb) scenario with no transmission distance has the lowest BER. For a given OSNR, the "without NLC" (w/o NLC) scenario has the highest BER, likely due to the accumulated SPM effect. This is because a higher OSNR signifies a stronger optical Kerr effect, leading to errors in the received data. The "with NLC" case has a slightly higher BER than the btb case, demonstrating NLC's effectiveness in mitigating NL effects and improving BER performance.

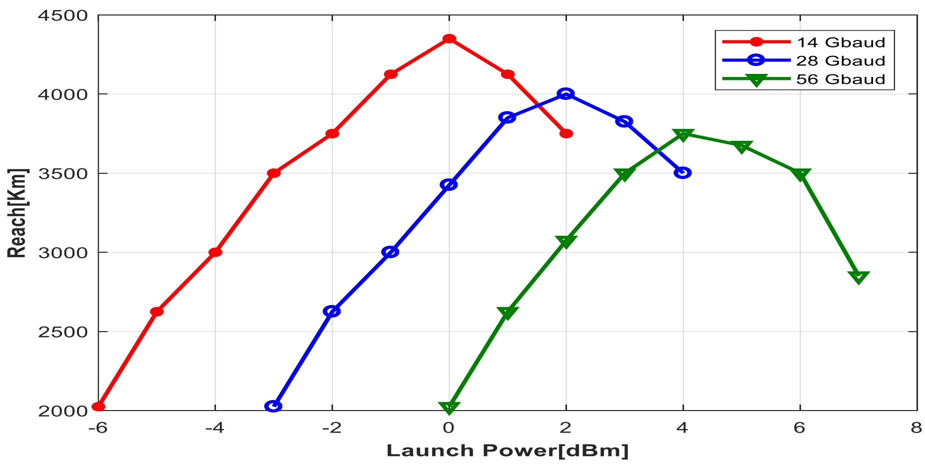


Figure III.8: *System reach as a function of the fiber launch power per channel for different values of symbol rate.*

To extend its reach, the DBP algorithm with optimal Nsteps should produce a larger performance improvement with high Baud-rate systems. This is because DBP is known to efficiently compensate for single-channel NL effects. Figure 3.10 illustrates the maximum transmission distance after DBP optimizes the number of steps per span, resulting in two, four, and eight steps per span for 14, 28, and 56 GBaud, respectively.

We observe that the accumulated optical noise limits performance at lower powers. The optimum launch power improves by 2 dB as the launch power increases.

We have extended the distance results to 5100 km, 4625 km, and 4275 km, respectively, for 14 GBaud, 28 GBaud, and 56 GBaud. A common characteristic of these curves is that the improvement in the maximum Q-factor may be modest.

The system achieves substantially better performance by 13.72%, 13.51%, and 12.28% for 14 GBaud, 28 GBaud, and 56 GBaud, respectively.

Note that when using only one step per span, the best-performing system is 14 GBaud, whereas the gain due to DBP is very small at 56 GBaud. The reason is that the optimum launch power is very high at 56 GBaud, which implies a highly NL propagation regime. As a result, one step per span in the DBP algorithm is not sufficient to properly account for the interaction between linear and NL effects in the fiber.

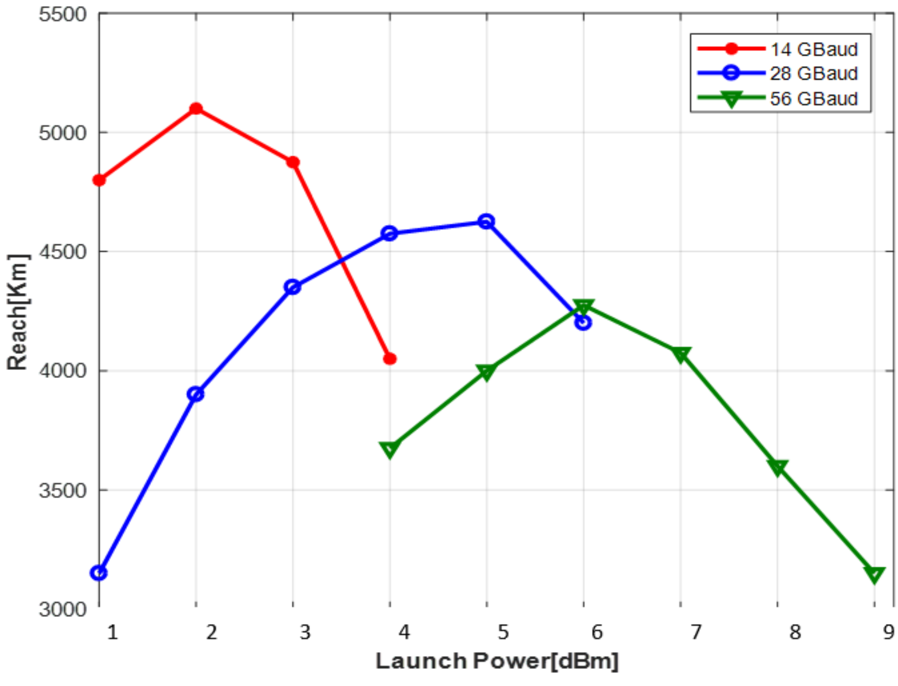


Figure III.9: *System reach as a function of the fiber launch power per channel for three different values of symbol rate.*

III.4 Conclusion

In this chapter, we analyzed the performance of the nonlinearity fiber compensation for the PDM-0.3RZ-QPSK system, considering the effects of phase self-modulation. We used the digital feedback algorithm as a mitigation technique in this single-channel transmission. We simulate using various symbol rates, including 14, 28, and 56 Gbaud.

We compared the system performance between DSPs with and without non-linearity compensation, evaluating it in terms of optimal launch power and binary error rates. The results show that performance improved after DBP configuration. The nonlinear threshold power was extended by 2 dB compared to the uncompensated case, with a binary error rate of 1.54×10-4 and a Q factor of 10.25 dB.

Furthermore, the results indicated that distance had a significant impact on compensation performance. Therefore, our study quantifies the maximum range at 5100 km. The PDM-0.3RZ-QPSK system and NLC worked together to boost the maximum reach by 13.72 % at 14 GBaud, 13.51 % at 28 GBaud, and 12.28 % at 56 GBaud.

Higher symbol rates can potentially increase data capacity, but they can also make you more susceptible to impairments.

General Conclusion

General Conclusion

In conclusion, the ever-growing demand for data capacity in optical communication systems necessitates the exploration of techniques to overcome limitations imposed by non-linear effects in optical fibers. This thesis looked into whether the Digital Backpropagation (DBP) method could help fix these problems in a PDM-0.3RZ-QPSK system.

We conducted numerical simulations to evaluate the impact of non-linearity and the effectiveness of DBP for different symbol rates (14, 28, and 56 Gbaud) over long transmission distances.

The performance was evaluated using metrics like BER (bit error rate) and Q-factor. The results demonstrate that DBP offers significant benefits in combating intrachannel non-linear SPM impairment. The application of DBP led to a 2 dBm increase in the non-linear power threshold at a target BER of 1.54×10^{-4}. Furthermore, we observed a 2.50 dB improvement in the Q-factor, indicating enhanced signal quality with distances up to 5100 km.

This thesis successfully shows that DBP has the potential to be used to make high-speed PDM-0.3RZ-QPSK optical communication systems work better. By mitigating the non-linear effect, DBP paves the way for increased data capacity and potentially longer transmission distances.

Future research should consider incorporating alternative techniques like machine learning algorithms (like deep neural networks) into NLC implementation, either as a complement or as a replacement for digital backpropagation (DBP), which could simplify the process and enhance transmission range. It is very important to look into higher-order modulation formats (16-QAM, 64-QAM) along with advanced multiplexing methods such as Dual-Polarization Modulation (PDM) in order to increase transmission capacity even more. However, implementing these advanced formats might introduce new challenges related to increased signal complexity and potential trade-offs in terms of system performance.

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