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Simulation and study of advanced WDM systems

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abstract:

This study aims to advanced WDM technologies, specifically coherent WDM and Nyquist-WDM, through simulations to evaluate their performance in high-speed optical networks.

The study begins with the fundamentals of coherent systems, including their advantages in sensitivity and spectral efficiency. The second part compares conventional DWDM with Nyquist-WDM, highlighting the improved spectrum utilization achieved through narrower channel spacing. Finally, the simulation results analyze key factors such as input power, bit rate, channel spacing, and optical fiber length using metrics such as bit rate (BER), optical noise reduction ratio (OSNR), and quality factor (Q-factor).

The results confirm that Nyquist-WDM, combined with coherent detection and digital signal processing (DSP), significantly improves system capacity and performance, providing guidance for future optical network design.

Keywords: Coherent Nyquist-WDM, High speed optical network, Nonlinear compensation, Digital signal processing, Spectral efficiency, Bit error rate.

الملخص:

تهدف هذه الدراسة إلى تسليط الضوء على تقنيات التعدد بتقسيم الطول الموجي المتقدمة، وبشكل خاص الأنظمة المتماسكة وWDM من نوع Nyquist، وذلك من خلال محاكاة لتقييم أدائها في الشبكات البصرية عالية السرعة.

تبدأ الدراسة ببيان أساسيات الأنظمة المتماسكة، مع توضيح مزاياها من حيث الحساسية وكفاءة استخدام الطيف. ثم يتم إجراء مقارنة بين أنظمة WDM التقليدية وأنظمة Nyquist-WDM، مع إبراز التحسين في استغلال الطيف الناتج عن تقليل التباعد بين القنوات.وأخيرًا، تتناول نتائج المحاكاة تحليلًا لعدد من العوامل المؤثرة مثل القدرة الداخلة، وسرعة نقل البيانات، وتباعد القنوات، وطول الألياف البصرية، وذلك باستخدام مؤشرات مثل معدل الخطأ في نقل البيانات، ونسبة تقليل الضوضاء في الإشارة الضوئية، ومعامل الجودة.

وقد أظهرت النتائج أن الجمع بين تقنية Nyquist-WDM والكشف المتماسك ومعالجة الإشارة الرقمية يؤدي إلى تحسين كبير في سعة النظام وأدائه، مما يساعد في توجيه تصميم الشبكات البصرية المستقبلية.

الكلمات المفتاحية: تقنية نايكويست المتماسكة لتقسيم الطول الموجي، الشبكة البصرية عالية السرعة، التعويض غير الخطي، معالجة الإشارة الرقمية، الكفاءة الطيفية، معدل خطأ البت.

Dedication

To Allah, the Almighty,

who lit my path with guidance and filled my heart with patience and strength all praise is due to Him, in every moment, in every breath.

To my dearest mother,

the heartbeat of tenderness, whose whispered prayers paved my way to success this work is a gift wrapped in the warmth of your endless love. You are the home when the world feels far away.

To my beloved father,

a quiet strength, a steady presence you were the guiding light in silence, the solid ground beneath my feet.

To my brothers and sisters,

who shared the laughter, the worries, and the quiet moments of hope you are the beautiful echo of family in every step of my journey.

To my faithful friends and fellow travelers,

who stood by me through the long nights and heavy days you are the unforgettable companions of this chapter, the true treasure I gained along the way.

Thank you so much for my sake

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*To my **beloved family**, I extend my heartfelt appreciation and love. Your endless support, silent prayers, and unwavering faith in me were the backbone of my strength and perseverance.*

*Last but not least, I would like to thank my **friends and fellow students**, with whom I shared not only academic efforts but also moments of camaraderie, support, and unforgettable memories.*

Thank you…

Summary

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WDM	Wavelength Division Multiplexing
GTE	General Telephone & Electronics Corporation
AT&T	American Telephone and Telegraph Company
GaAs	Gallium Arsenide
EDFA	Erbium-Doped Fiber Amplifier
SDM	Space Division Multiplexing
PRBS	Pseudo-Random Bit Sequence
ISI	Intersymbol Interference
$LiNbO_3$	Lithium Niobate
MZM	Mach-Zehnder Modulator
BW	Bandwidth
PDM	Polarization Division Multiplexing
MDM	Mode Division Multiplexing
PBC	Polarization Beam Combiner
PBS	Polarization Beam Splitter
MMF	Multimode Fiber
DSP	Digital Signal Processing
SPM	Self-Phase Modulation
XPM	Cross-Phase Modulation
FWM	Four-Wave Mixing
SBS	Stimulated Brillouin Scattering
SRS	Stimulated Raman Scattering
LO	Local Oscillator
IF	Intermediate Frequency
ADC	Analog-to-Digital Converter
FDE	Frequency-Domain Equalization
DBP	Digital Backpropagation
CMA	Constant Modulus Algorithm
MIMO	Multiple-Input Multiple-Output
FFT	Fast Fourier Transform
FEC	Forward Error Correction
BER	Bit Error Rate
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
OSNR	Optical Signal-to-Noise Ratio
OSA	Optical Spectrum Analyzer
ASE	Amplified Spontaneous Emission
Pre-FEC	Pre-Forward Error Correction

Db	Data rate per optical carrier
FDM	Frequency Division Multiplexing
CWDM	Coarse Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
AWGs	Arrayed Waveguide Gratings
Nyquist-WDM	Nyquist Wavelength Division Multiplexing
Quasi-Nyquist WDM	Quasi-Nyquist Wavelength Division Multiplexing
Super-Nyquist WDM	Super-Nyquist Wavelength Division Multiplexing
RC	Raised Cosine (filter)
SE	Spectral Efficiency
ICI	Inter-Channel Interference
SSMF	Standard Single-Mode Fiber
16-QAM	16-Quadrature Amplitude Modulation
FIR	Finite Impulse Response
MAC	Multiply-Accumulate
DD-LMS	Decision-Directed Least-Mean-Square
DA	Distributed Arithmetic
SNR	Signal-to-Noise Ratio
GVD	Group Velocity Dispersion
NZDSF	Non-Zero Dispersion-Shifted Fiber
IQ	In-phase and Quadrature
NLC	Nonlinear Compensation
SD-FEC	Soft-Decision Forward Error Correction
HD-FEC	Hard-Decision Forward Error Correction

General introduction

General introduction

The surge in global data consumption, propelled by the swift advancement of cloud computing, high-definition video streaming, and the deployment of 5G networks, demands the growth of optical communication technologies. Among these, Wavelength Division Multiplexing (WDM) has emerged as a foundational technique, enabling the simultaneous transmission of multiple data channels over a single optical fiber. This dramatically boosts bandwidth without necessitating the deployment of additional fiber infrastructure. As modern communication networks scale toward terabit-per-second capacities, the design and refinement of advanced WDM systems have become more vital than ever.

This thesis explores the simulation and performance analysis of two significant WDM architectures: conventional Dense WDM (DWDM) and Nyquist-WDM. Special attention is given to coherent detection techniques and digital signal processing (DSP), which play an essential part in enhancing the system performance. The core objective is to gain a deeper understanding of these architectures, pinpoint the primary factors that limit performance, and assess how various system parameters affect spectral efficiency and signal fidelity. Through simulation-based analysis, the effort seeks to expose understanding of system behavior under various, real-world operating environments.

The thesis is organized into the following chapters:

- **Chapter I** provides an overview of WDM systems, introducing coherent detection principles, critical system components, and prevailing challenges.
- **Chapter II** delivers a comparative analysis of DWDM and Nyquist-WDM, highlighting their spectral efficiencies, advantages, and implementation considerations.
- **Chapter III** presents simulation results, evaluating key performance indicators and comparing the two architectures across a range of scenarios.

The thesis concludes by summarizing the principal findings and discussing their implications for the next generation of high-capacity optical communication systems.

Chapter I:
Coherent optical WDM system fundamentals

I.1 Introduction

The rapid growth of internet traffic, cloud computing, and high-speed data services has driven the demand for greater transmission capacity in optical communication networks. Coherent optical Wavelength Division Multiplexing (WDM) systems have become an important technology to meet these needs, providing better use of bandwidth, clearer signals, and faster data speeds.

This chapter provides a comprehensive overview of the fundamental principles underpinning coherent optical WDM systems. It explores key components such as lasers, modulators, coherent receivers, and digital signal processing (DSP) techniques.

I.2 The evolution of fiber-optic transport networks

Fiber optic communication started with successful field tests in 1977. Within a short time, telephone companies like GTE, AT&T, and the UK Post Office were transmitting live telephone traffic over multimode fibers at various speeds. Similar efforts were underway in other European countries. The evolution of fiber-optic communication systems began around 1975 and has progressed through several generations [1-3]:

- **First Generation (1977–1980):** These systems operated at 0.8 µm using GaAs semiconductor lasers, with commercial systems emerging in 1980. They supported bit rates of 45 Mb/s and allowed repeater spacing of up to 10 km.
- **Second Generation (Early 1980s):** Due to multimode fiber dispersion, early systems had bit rate limitations below 100 Mb/s. The issue was resolved with single-mode fibers, enabling a 1981 lab demonstration of 2 Gb/s over 44 km. By 1987, commercial systems achieved 1.7 Gb/s with 50 km repeater spacing.
- **Third Generation (1990):** These systems operated at 2.5 Gb/s and had a potential for up to 10 Gb/s. They used dispersion-shifted fibers and single-mode lasers but required electronic repeaters every 60–70 km.
- **Fourth Generation (Mid-1990s):** This generation introduced optical amplification and WDM, significantly increasing repeater spacing and bit rates. By 1996, systems achieved 5 Gb/s over 11,300 km, with commercial transatlantic and transpacific cables becoming available.
- **Fifth Generation (Late 1990s):** Focused on expanding the WDM wavelength range beyond the conventional C band (1.53–1.57 µm) to include the L and S bands. Raman amplification supported signals across all bands, and "dry fiber" was developed to minimize losses across a broad wavelength range (1.30–1.65 µm).

Each generation marked significant advancements in bit rates, repeater spacing, and wavelength utilization, driven by innovations in fiber technology and amplification techniques.

- **Sixth Generation (present day) :**Researchers are now pushing fiber optic technology to new heights, focusing on three main areas: expanding wavelength capacity, developing multicore fibers, and advancing ultra-high-speed technologies. By extending wavelength bands such as the L-band (1570-1625nm) and S-band (1460-1530nm), and integrating new Raman amplification with existing Erbium-doped fiber amplifiers, the potential capacity has been significantly boosted.

Innovative multi-core and few-mode fiber designs allow different signals to be sent simultany through separate cores or modes in one fiber, and space division multiplexing provides a significant increase in capacity. At the forefront of research, scientists are exploring revolutionary concepts, like spiraling nanophotonic devices, which manipulate light to achieve bit rates 100 times faster while layering multiple signals using space, wavelength, and polarization techniques.

As tenth-generation systems begin to take shape, the future of fiber optics holds immense promise. Performance has doubled every six months over the past 50 years, and this rapid progress shows no signs of slowing down.

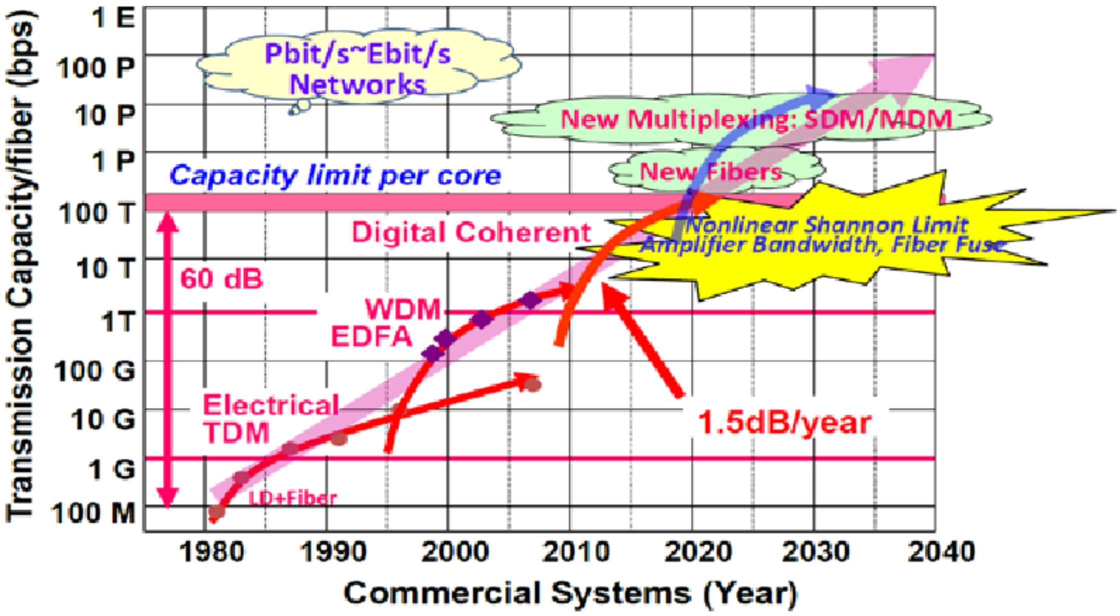


Figure I.1: Evolution of optical transmission technologies.

I.3 Fundamentals of coherent optical systems

Fiber-optic systems utilize light to carry information across optical fibers from one location to another. Similar to all communication systems, the physical layer of fiber-optic systems can be broken down into three main components: the transmitter, the channel, and the receiver. The structure of a coherent optical system is illustrated in Figure I.2.

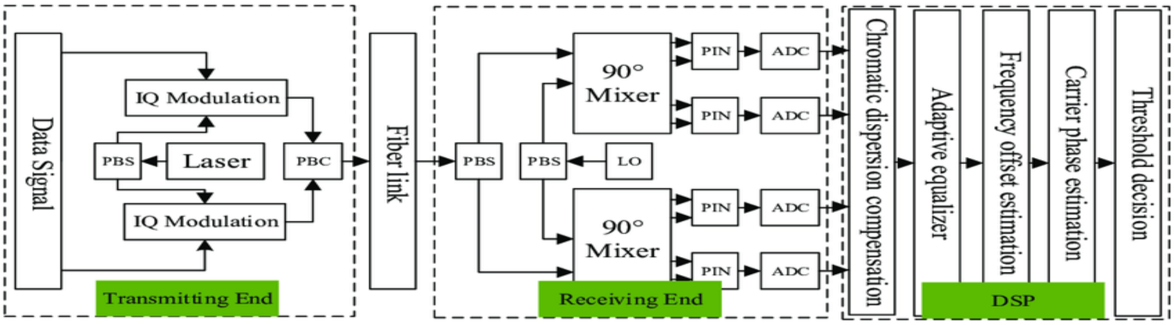


Figure I.2: Coherent optical communication system structure diagram.

I.3.1 Transmitter

The optical transmitter is responsible for converting electrical signals into optical signals that can be transmitted through optical fibers. Think of it as the device that takes your electronic data and transforms it into pulses of light. It includes the following:

I.3.1.a Bit sequence

A bit sequence is the source of data or information. Often referred to as multiple-bits-per-symbol or pseudo-random bit sequences (PRBS), these sequences enhance spectral efficiency and increase data rates. They encode data information and are typically generated with a defined period and bit rate.

PRBS helps mitigate common challenges in optical communication systems, such as phase noise and intersymbol interference (ISI). Additionally, they are vital for the receiver's error correction process, enabling precise data recognition and accurate decoding of transmitted information. [4]

I.3.1.b Generation of electrical signals

The process begins by encoding data into binary digits, which serves as the initial step in generating electrical signals. These signals are then transformed into symbols according to the chosen modulation format. The symbols, which are independent and identically distributed, are subsequently shaped into a pulse to create an oversampled representation that fully preserves the original information. [5]

$$\mathbf{u_E(t)} = \sum_{-\infty}^{\infty} \mathbf{S_k\, g(t - kT_s)}$$

Where S_k represents the symbol at the time instant $\mathbf{kT_s}$ and **g(t)** denotes the pulse shape, the bandwidth of the resulting signal is regulated by the pulse shaping filter. [6]

I.3.1.c The laser

The laser diode is the heart of the optical transmitter, responsible for generating the light that carries the data. It converts an electrical signal into a modulated optical signal. By varying the current flowing through the diode, the intensity of the emitted light is changed, thus encoding the data onto the light wave. [7] [8]

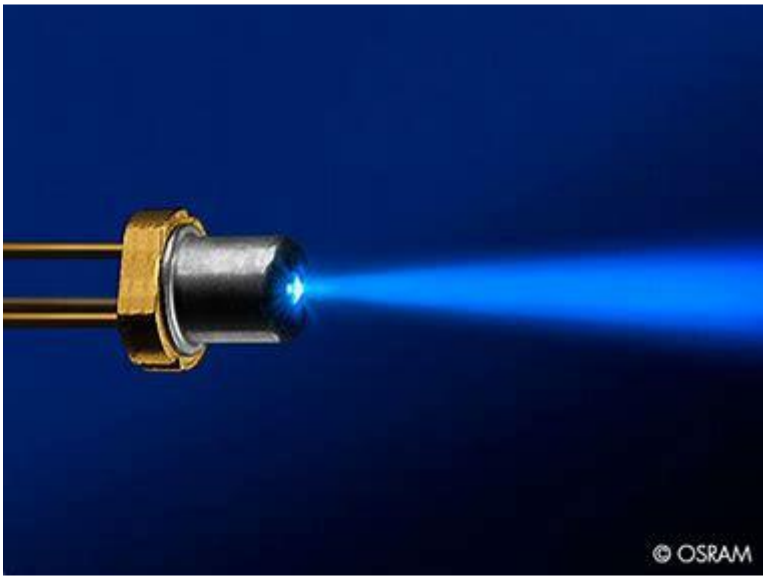


Figure I.3: Laser diode.

I.3.1.d The external modulation

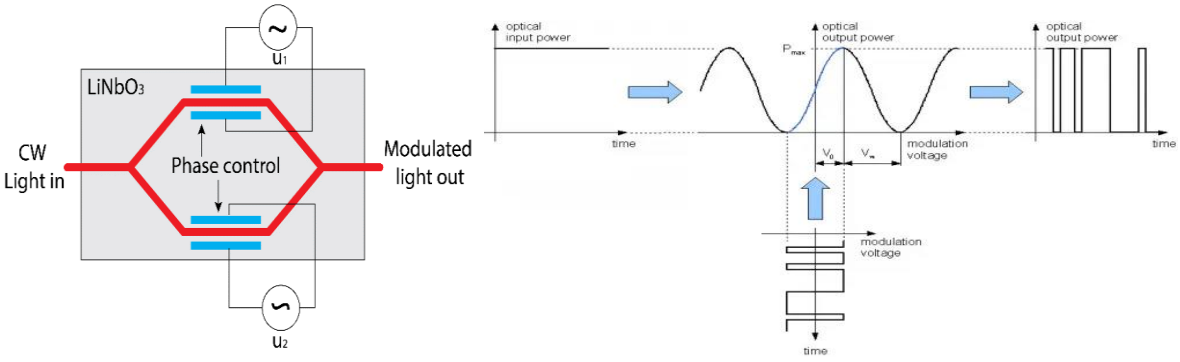
The optical part of high-order modulation transmitters depends on one or more basic external optical modulator designs, and the speed and quality of the output signal are greatly affected by the materials (like LiNbO3 (lithium niobate)) and technology used in these modulators.

A key example of such a modulator is the Mach-Zehnder Modulator (MZM), a highly versatile external modulator widely used in radio-on-fiber systems. The MZM comes in single-drive and dual-drive versions, and its flexibility comes from being able to control two electrical inputs separately, which lets it create many different types of optical modulation formats.

An input waveguide in its structure splits into two nonlinear waveguide interferometer arms, which later recombine at the optical output. The nonlinear medium in the MZM allows for important interactions between electrical and optical fields, making it essential for advanced modulation systems. [9]

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n L = \pi\frac{V}{V_\pi}$$

Where λ is the wavelength of the light, L is the length of the arms, and $V\pi$ represents the voltage that causes a phase shift of π rad. [5]



(a) (b)

Figure I.4: (a) Scheme, (b) Principle of a Mach-Zehnder modulator.

I.3.1.e Multiplexing techniques

Multiplexing is a technique that combines multiple signals into a shared channel, enabling the efficient utilization of the full capacity of optical links. Traditionally, it was employed to distribute the limited bandwidth (BW) of a medium among multiple transmitters. The emphasis now is on making the most of the enormous amount of available bandwidth in the context of optical networks.

Recent improvements in important multiplexing methods, like wavelength division multiplexing (WDM), polarization division multiplexing (PDM), space division multiplexing (SDM), and mode division multiplexing (MDM), have shown how essential they are for increasing the capacity of optical links.

These developments highlight the importance of advancing hybrid-multiplexing techniques, which combine multiple approaches to support more channels and further optimize the performance of optical communication systems. [10]

A. Wavelength division multiplexing

Wavelength-division multiplexing (WDM) is a technique that mitigates the inherent mismatch between optical and electronic bandwidths. A detailed analysis of WDM is presented in Section II.3.

B. Polarization division multiplexing

Polarization division multiplexing (PDM) enhances spectral efficiency by transmitting data symbols over two orthogonal polarization states, effectively doubling the capacity of optical transmission compared to single-polarization systems [11].

In PDM, a polarization beam combiner (PBC) merges the two polarization states into a single optical beam for transmission. At the receiver, a polarization beam splitter (PBS) separates the orthogonal states, allowing independent demodulation of each data stream. Figure I.5 illustrates a typical PDM system, demonstrating the multiplexing and demultiplexing of orthogonal polarization states to establish independent data channels [12].

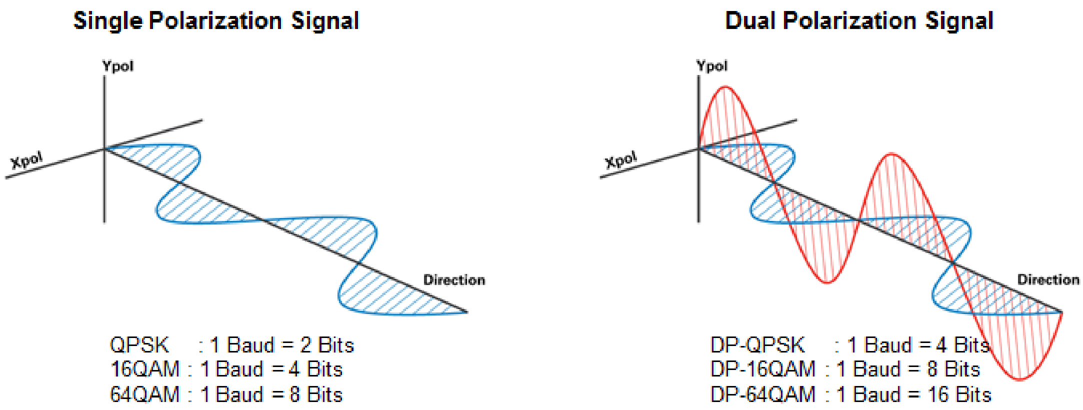


Figure I.5: Orthogonal polarization.

I.3.2 Principle of light propagation in optical fibers

Light propagation in optical fibers relies on the interaction between two coaxial cylindrical layers: the core and the cladding. Although the cladding is not strictly necessary for guiding light, it plays essential practical roles, including:

- Protecting the core surface from defects,
- Preventing refractive index variations caused by external contact or contamination, and
- Reinforcing the fiber's mechanical durability.

The core is designed with a slightly higher refractive index than the cladding. When light enters the core at an angle exceeding the critical angle (determined by Snell's law), it becomes trapped within the core due to total internal reflection at the core-cladding boundary. This mechanism ensures efficient, low-loss propagation over long distances.

Light propagation in optical fibers is governed by electromagnetic wave modes, which define distinct spatial patterns of the electric and magnetic fields. The fiber supports a finite number of these modes, determined by the material and structural properties of the fiber, as well as the wavelength of the light.[13]

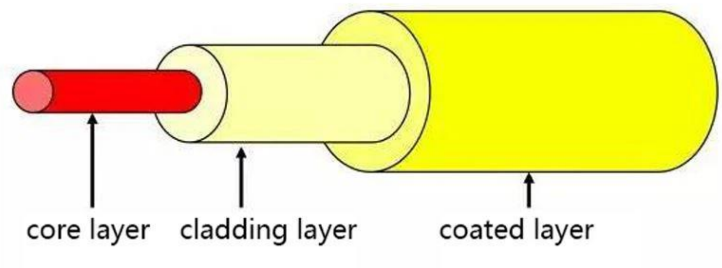


Figure I.6: The structure of the optical fiber.

Optical fibers can be categorized into two main types based on their diameters and how they propagate light wavelengths.

I.3.2.a Single-mode fibers

In single-mode fiber, only one light mode is transmitted through the fiber, which typically has a diameter ranging from 8.3 to 10 microns, as illustrated in Figure 1.7. Since only a single mode of light propagates, the issues commonly associated with multimode fiber, such as modal dispersion, are eliminated. This technique allows for higher transmission rates and makes single-mode fiber suitable for long-distance communication.

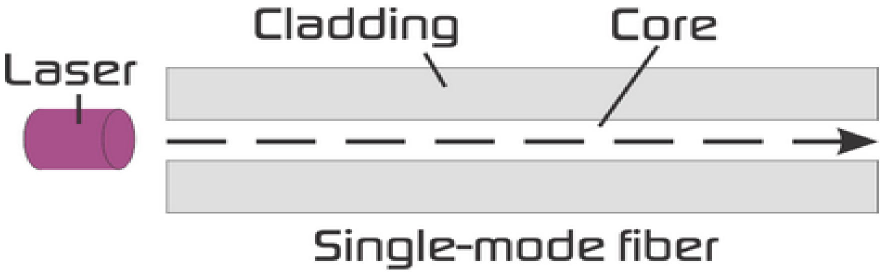


Figure I.7: The structure of the single mode fiber.

I.3.2.b Multimode optical fibers

Multimode fiber (MMF) was the first type of optical fiber to be commercialized. It features a significantly larger core compared to single-mode fiber, enabling hundreds of light modes to propagate simultaneously. MMF remains the dominant solution for short-reach applications, including local area networks, data center interconnects, and building cabling systems, where its cost-effectiveness and ease of use provide significant practical benefits. Table I.1 shows a clear comparison between multimode step-index and graded-index fibers, pointing out their main features and how they perform differently [14].

Feature	Step-Index Fiber	Graded-Index Fiber
Core Diameter	Typically around 100 microns	Typically 50, 62.5, or 100 microns
Refractive Index Profile	Core (n_1) has a constant refractive index, higher than cladding (n_2)	Refractive index decreases gradually from the center to the edges of the core
Light Propagation	Multiple light modes propagate, leading to modal dispersion	Light rays bend inward, reducing modal dispersion
Bandwidth	Lower bandwidth due to modal dispersion	Higher bandwidth compared to step-index fibers
Transmission Distance	Short-distance transmissions	Medium-range applications
Operating Wavelengths	850 nm and 1300 nm	Similar wavelengths (850 nm and 1300 nm)
Performance	Inferior to graded-index and single-mode fibers	Superior to step-index fibers but still below single-mode fibers

Table I.1: Comparison of multimode step-index and graded-index fibers.

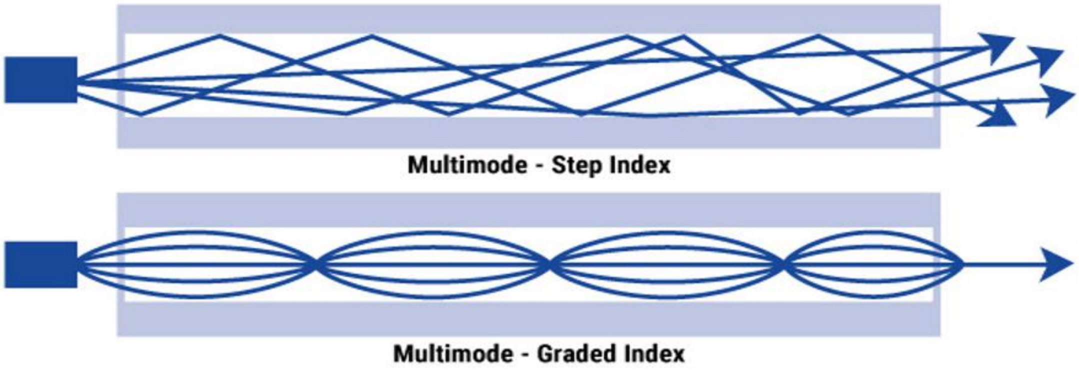


Figure I.8: Types multimode optical fiber.

I.3.2.c Impairments of the optical channel

The performance of optical communication systems is often compromised by various impairments that affect optical fiber channels. These impairments, which hinder signal transmission, can primarily be classified into two main categories.

A. Fiber linear effects

The term "linear effects" refers to transmission degradations that do not depend on the signal itself but rather result from the linear response of the fiber material to the electromagnetic excitation induced by the signal via susceptibility. Today, specific algorithms integrated into a digital signal processing (DSP) unit at the receiver can correct the majority of these linear effects. We distinguish three main effects among these: attenuation, chromatic dispersion, and polarization mode dispersion. [5]

1. Attenuation

Attenuation refers to the loss of signal power as it travels through the fiber, primarily caused by intrinsic material absorption, extrinsic impurities absorption, and scattering.
Silica fiber, with its remarkably low attenuation of approximately 0.2 dB/km, is well suited for long-distance transmission. This low attenuation is particularly evident in two wavelength regions, making silica fiber an ideal medium for communication.

The first region is the O-band, centered at $\lambda = 1300$ nm, which was initially favored in optical systems due to its low dispersion. The second region, the C-band, centered at $\lambda = 1550$ nm, is predominantly used in modern systems. The C-band offers lower attenuation than the O-band and provides a broad bandwidth of 3.6 THz, spanning from $\lambda = 1536$ nm to $\lambda = 1565$ nm, making it highly efficient for contemporary optical communication. [15]

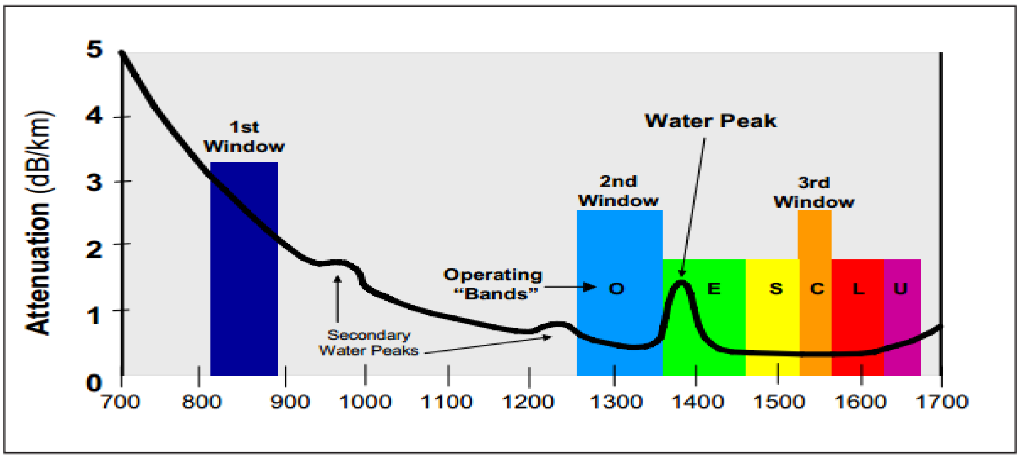


Figure I.9: Attenuation rate of optical fiber as a function of the wavelength.

2. Dispersion

Dispersion refers to the spreading of light pulses as they travel through an optical fiber. This phenomenon occurs due to factors such as numerical aperture, core diameter, refractive index profile, wavelength, and laser linewidth, which collectively cause the pulse to broaden as it propagates. The extent of dispersion increases with the length of the fiber. The primary consequence of dispersion on fiber optic systems is known as Intersymbol Interference (ISI). ISI arises when the broadening of pulses causes them to overlap at the output, making it difficult or impossible to distinguish between individual pulses and, thereby, degrading the system's performance.

B. Fiber nonlinear effects

Nonlinear impairments, another type of signal distortion seen in optical fiber channels, are more common in transmissions over long distances. Changes in propagation speed as a function of signal intensity and wavelength give rise to nonlinear effects. These consequences may show up as

- ✓ Signal attenuation that increases with higher transmitted power.
- ✓ The generation of new wavelengths.

The primary causes of these nonlinear effects are described as:

1. Kerr effect

The Kerr effect is typically responsible for nonlinear degradation encountered by an optical signal during propagation. An illustration of this phenomenon is how the intensity of an optical signal may modify a material's refractive index. The equation for the refractive index, n, influenced by the Kerr effect in an optical medium is as follows:

$$n = n_0 + n_2 \mid E \mid^2 = n_0 + n_2 I$$

Where:

E is the electric field, n_0 represents the linear refractive index. n_2 is the nonlinear refractive index coefficient (also known as the Kerr coefficient), which depends on the material, and I denotes the intensity of the signal.

In silica, the typical value of n_2 is approximately $2.6 \times 10^{-20}\ \mathrm{m^2/W}$ at 1550 nm for a single-mode fiber, with little variation across different fiber types.

The nonlinear coefficient, represented by γ, quantifies the Kerr effect responsible for these nonlinear phenomena and is defined as:

$$\gamma = \frac{n_2\, \omega}{c\, A_{\mathrm{eff}}}$$

where:

ω is the angular frequency of the signal. c is the speed of light in vacuum. A_{eff} is the effective area of the fiber.

The parameter γ measures the fiber's sensitivity to nonlinear effects that may occur during the propagation of a pulse. In standard single-mode fibers, its typical value is around $2\,\mathrm{W^{-1}km^{-1}}$ for 1500 nm. The nonlinear length parameter L_{NL} is used to assess the impact of nonlinear effects on a pulse with peak power as it propagates through a fiber with a nonlinear coefficient.

$$L_{\mathrm{NL}} = \frac{1}{\gamma P_0}$$

Self-Phase Modulation (SPM)

The most basic third-order nonlinear process is self-phase modulation, which is fundamentally a temporal phenomenon when treated within a plane-wave framework. A phenomenon known as self-phase modulation occurs when the refractive index changes over time. Specifically, during propagation under the assumptions of the slowly changing envelope approximation and an instantaneous medium response the pulse accumulates a nonlinear phase given by:

$$\Phi_{NL}(t) = \frac{2}{\lambda} n_2\, L\, I(t)$$

This time-dependent phase alters the pulse's spectral width, shape, and the concept of instantaneous frequency, expressed as:

$$\omega(t) = \omega_0 - \delta\omega(t)$$

$$\delta\omega(t) = -\frac{d}{dt}\Phi_{NL}(t)$$

- **Cross-Phase Modulation (XPM)**

Cross-phase modulation (XPM) relies on the same basic concept as self-phase modulation (SPM), but it happens in the presence of several waves traveling inside the fiber. These waves may have distinct wavelengths or the same wavelength with varying polarizations. Consequently, the refractive index perceived by one wave is varied not only by its strength but also by the intensity of the other waves present.

For example, in a system with two wavelengths, λ_1 and λ_2, the refractive index observed by the wave at λ_1 is given by:

$$n = n_0 + n_2[I(\lambda_1) + 2\, I(\lambda_2)]$$

Here, the term $I(\lambda_1)$ represents the contribution from self-phase modulation (SPM), while the term $2I(\lambda_2)$ corresponds to cross-phase modulation (XPM). In this scenario, XPM is twice as strong as SPM. Cross-phase modulation significantly influences wavelength-division multiplexed (WDM) optical links.

- **Four-Wave Mixing (FWM)**

Four-wave mixing (FWM) is a nonlinear process in which three continuous waves, having carrier frequencies ω_i, ω_j, and ω_k, interact to generate a fourth wave centered at the frequency:

$$\omega_1 = \omega_i + \omega_j - \omega_k.$$

The new frequencies produced by FWM are referred to as intermodulation products. The nonlinear polarization that gives rise to this intermodulation product is expressed as:

$$P_{NL}\left(\omega_i + \omega_j - \omega_k\right) = \frac{3}{4}\, \epsilon_0\, \chi^{(3)}\, E_i E_j E_k,$$

Where ϵ_0 is the permittivity of free space, $\chi^{(3)}$ is the third-order nonlinear susceptibility, and E_i, E_j, and E_k are the electric fields of the interacting waves.

The efficiency of the four-wave mixing process is maximized when the phase mismatch parameter is equal to zero [16]:

$$\Delta\beta = \beta_i + \beta_j - \beta_k - \beta_1 = 0$$

2. Stimulated scattering effects

In optical fibers, stimulated scattering effects become prominent at elevated power levels, resulting in the conversion of signal energy into undesirable new optical waves via interaction with the fiber medium.

The two principal types are Stimulated Brillouin Scattering (SBS), which occurs due to interaction with acoustic waves exceeding a threshold, primarily scattering light in reverse and yielding a modest frequency shift; and Stimulated Raman Scattering (SRS), which results from interaction with molecular vibrations surpassing a threshold, capable of scattering light in both forward and backward directions and producing a significantly larger frequency shift (approximately 13 THz in silica) [17].

C. Optical amplifier

The growth of optical communications systems experienced a revolution with the creation and industrial manufacturing of optical amplifiers in the late 1980s. These devices developed as a feasible alternative to the sophisticated optoelectronic repeater-regenerators that were previously needed. Such repeater-regenerators, which must work at extremely high data rates, are costly, complicated, and tough to construct and interface. Optical amplification ignited a genuine revolution in telecommunications, especially when paired with wavelength-division multiplexing (WDM). In reality, an optical amplifier may concurrently raise the signal on all N wavelengths of a multiplexer without distorting the useable signal unlike regeneration, which demands as many regenerators as there are wavelengths.

1. Advantages of optical amplification

Optical amplifiers provide various advantages compared to repeater-regenerators, which must be configured for a specified data rate. In an optical amplifier, the bandwidth is no longer restricted by electronics and may reach many hundreds of gigahertz. This method permits the amplification of signals whose wavelengths fall within the amplifier's sensitivity range, regardless of the transmission rate and modulation style utilized. However, a negative is that optical amplification puts noise into the optical signal as it goes through the device (see Figure I.10).

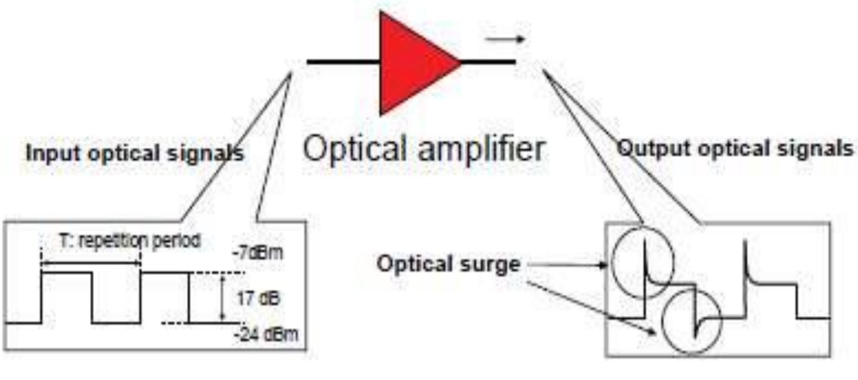


Figure I.10: Principle of the optical amplifier

2. Erbium-Doped Fiber Amplifier (EDFA)

Erbium-Doped Fiber Amplifiers (EDFAs) are the primary devices for amplifying optical signals, employing optical pumping to mitigate transmission loss and distance challenges. Their advancement was essential for facilitating high-capacity, high-speed wavelength-division multiplexing systems, especially within the 1550 nm range, and reliable, economical components are now extensively accessible within the 1550-1600 nm spectrum. The essential components of an EDFA comprise an erbium-doped optical fiber (the gain medium for approximately 1.55 µm), a pump laser source to excite the erbium ions, and a multiplexer to effectively amalgamate the pump light and the signal within the doped fiber.

The amplification process relies on stimulated emission from erbium ions. The pump laser excites these ions to a higher energy state. When signal photons pass through, they stimulate the excited ions to release identical photons (same frequency, phase, polarization, direction), thus amplifying the original signal. EDFAs can achieve significant gain (up to 40 dB) with high output power (~30 dBm). However, some ions also de-excite via spontaneous emission, creating random photons that constitute noise and must be filtered out before detection. [18]

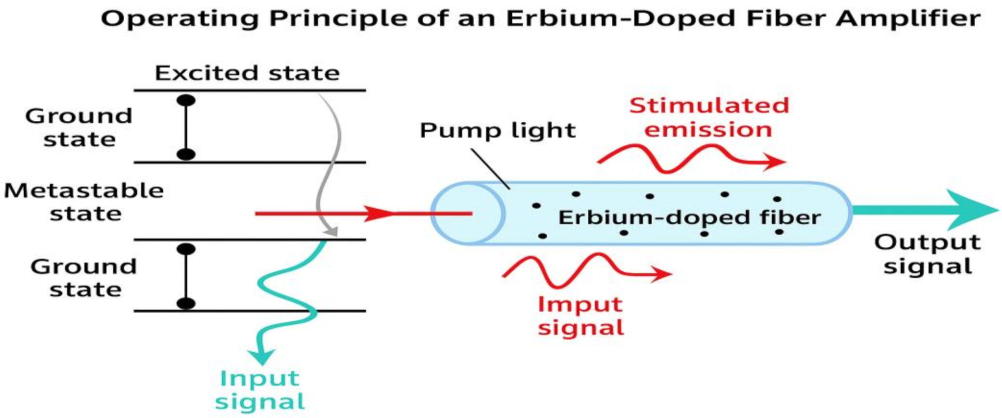


Figure I.11: Operating principle of an Erbium-Doped Fiber Optical.

I.3.3 Coherent receiver with digital signal processing

Coherent receivers in optical communication systems integrate digital signal processing (DSP) techniques. They typically comprise several functional modules, each responsible for a specific, critical task. Figure I.12 below presents the block diagram of a coherent receiver.

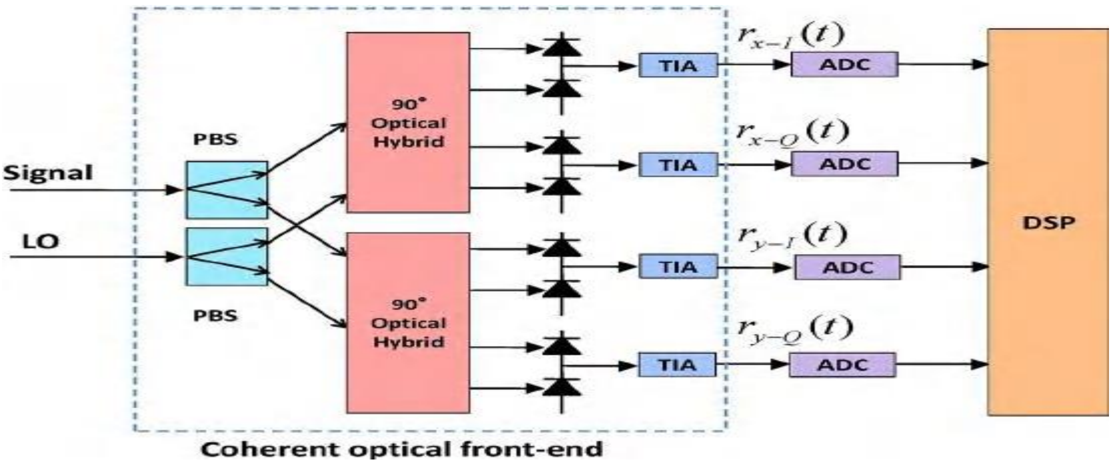


Figure I.12: Block diagram of the optical receiver comprising coherent detection and DSP blocks.

I.3.3.a Coherent receiver components

A. Coherent detection

Coherent detection is essential approach in current optical communication systems that exploits the mixing of the incoming optical signal with a strong local oscillator (LO) signal to boost detection sensitivity. By combining the optical power of the weak signal with that of the LO-which is often considerably higher-the resultant photocurrent is greatly boosted, allowing the detection of extremely weak signals without depending on several optical amplifiers along the transmission channel.

There are three basic kinds of coherent receivers as mention in Figure I.13 displays this, each defined by the connection between the LO frequency and the signal frequency.

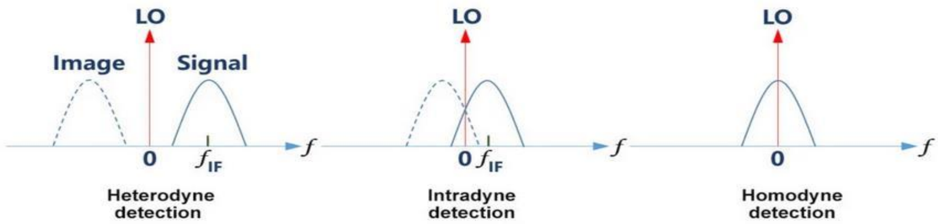


Figure I.13: Forms of coherent detection.

- **Homodyne detection** simplifies receiver design by tuning the local oscillator (LO) to the exact frequency of the incoming signal, directly creating a baseband signal. However, it demands a very stable LO due to high sensitivity to phase noise.
- **Heterodyne detection** mixes the signal with a slightly offset LO, generating an intermediate frequency (IF) signal easier to process and offering better resilience to LO phase noise, at the cost of increased system complexity due to added frequency conversion components.
- **Intradyne detection** is used when the signal bandwidth is large, employing an LO close to the signal frequency to keep the mixed signal in the baseband. This approach offers a simpler design and lower phase noise sensitivity than heterodyne detection, though it might not be as spectrally efficient.

The selection of a coherent detection scheme homodyne, heterodyne, or intradyne depends on various criteria, including system requirements, performance objectives, design complexity, and cost concerns. Each strategy provides distinct benefits and trade-offs, making them appropriate for diverse applications in high-speed, long-haul optical communications. [19]

I.3.3.b Digital signal processing blocks

In a coherent optical receiver, the DSP chain evaluates digitized samples from the photodiodes to rectify various transmission impairments and ultimately recover the sent data. The DSP design is divided into the following fundamental functional components, as depicted in Figure I.14, which provides a schematic representation of the DSP architecture.

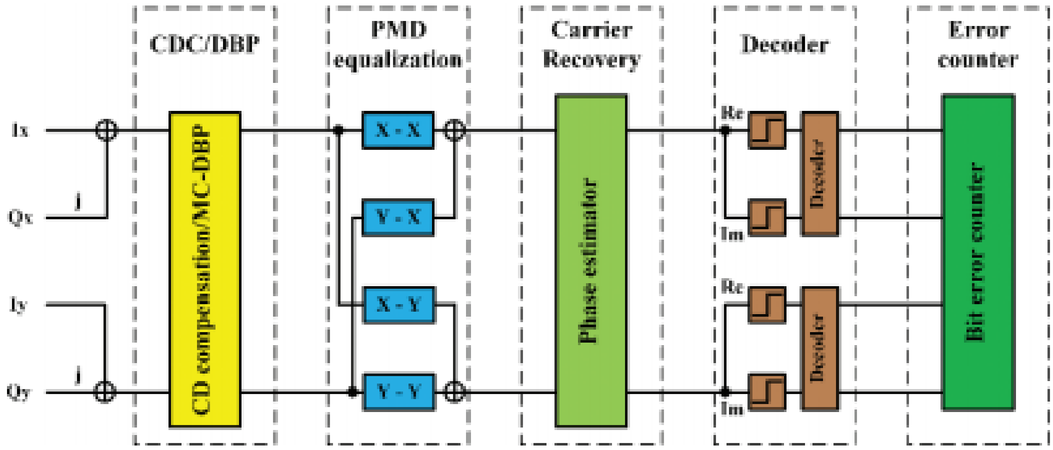


Figure I.14: Digital signal processing blocks.

A. Symbol clock synchronization

This block is crucial for aligning the receiver's sampling times with the incoming data symbols, as timing errors during analog-to-digital conversion can cause misalignment, particularly between polarization channels. To address this, the Analog-to-Digital Converters (ADCs) sample the analog photocurrents at a rate significantly higher than the symbol rate, typically twice, with high resolution (6-8 bits). This oversampling prevents aliasing, minimizes quantization noise, and provides a finer temporal resolution, which is essential for implementing precise digital synchronization algorithms to correct for any timing mismatches and ensure accurate data recovery.

B. Equalization and polarization demultiplexing

These parts are essential for mitigating transmission impairments. Equalization techniques, employing adaptive filtering algorithms like frequency-domain equalization (FDE) for linear distortions or digital backpropagation (DBP) for nonlinear effects, compensate for channel impacts. Simultaneously, Polarization Demultiplexing addresses the mixing of polarization components (*Ex* and *Ey*) caused by channel limitations, using algorithms to separate these streams. Commonly, blind equalizers such as the Constant Modulus Algorithm (CMA) and multiple-input multiple-output (MIMO) equalization, often in a "butterfly" configuration, are jointly applied to counteract inter-symbol interference and other linear transmission limitations, effectively restoring the original signal and ensuring high-quality data recovery across both polarization channels.

C. Frequency and carrier phase recovery

A major issue in coherent detection is the residual frequency offset between the receiver's local oscillator and the transmitter's carrier frequency, resulting in continual phase rotation and possible mistakes. To mitigate this, the digital signal processor initially assesses the frequency offset utilizing methods such as differential phase analysis or FFT-based spectrum analysis. Subsequent to rectifying the frequency discrepancy, it utilizes carrier phase recovery methods to mitigate the residual phase noise, predominantly resulting from the limited linewidths of the lasers. The two-step procedure of frequency offset estimation followed by phase noise compensation guarantees precise alignment of the received symbols for dependable detection.

D. Error correction

Even after precise timing synchronization, equalization, and phase recovery, the received signal can still contain errors due to noise and remaining distortions. To improve data integrity, the error correction block applies forward error correction (FEC) algorithms. By adding redundant parity bits to the transmitted data, FEC enables the receiver to detect and sometimes correct errors, using either soft-decision methods that consider symbol reliability or hard-decision methods. This crucial error correction stage significantly reduces the bit error rate (BER), thereby enhancing the overall performance and reliability of the optical communication system.

E. Data recovery

Following error correction, the final stage of the digital signal processing chain, data recovery, focuses on retrieving the original transmitted information by converting the corrected symbols back into a stable digital bit stream. This process involves two key steps: mapping, where the processed symbols are translated back into their corresponding binary sequences based on the modulation format (e.g., QPSK, QAM), and de-interleaving, which rearranges the data to its original order if interleaving was used during transmission to mitigate burst errors. These steps ensure that the reconstructed bit stream is in the correct sequence for accurate decoding and further utilization [20].

I.4 System performance

With the ongoing advancements in optical communication technology, it is imperative to possess precise and dependable methods for evaluating the performance of optical networks.

Metrics including bit error rate (BER), Q Factor, and optical signal-to-noise ratio (OSNR) are frequently employed for this objective.

I.4.1 The bit error rate

The Bit Error Rate (BER) is a fundamental metric used to assess the performance of a digital communication system. It represents the probability that a transmitted bit is received in error. In other words, it is the ratio of the number of erroneous bits to the total number of transmitted bits:

$$\text{BER} = \frac{\text{Number of Erroneous Bits}}{\text{Total Number of Transmitted Bits}}$$

A lower BER indicates a higher quality and more reliable communication link. In optical systems, BER is influenced by factors such as noise, signal distortion, and various impairments during transmission.

I.4.2 Q Factor

The Quality Factor (Q) provides a measure of the signal quality at the receiver by quantifying how distinctly the binary '1's and '0's are separated in the presence of noise. It is defined as the difference between the mean levels for logical '1' and '0', divided by the sum of the noise standard deviations associated with these levels:

$$Q = \frac{v_1 - v_0}{\sigma_1 + \sigma_0}$$

Here, v_1 and v_0 are the average signal levels for a binary '1' and a binary '0', respectively, while σ_1 and σ_0 represent the noise standard deviations around these levels. Under the assumption that the noise follows a Gaussian distribution, the relationship between BER and Q Factor given by:

$$\text{BER} = \frac{1}{2}\, erfc\left(\frac{Q}{\sqrt{2}}\right)$$

This equation links the measurable Q Factor to the system's BER, providing a convenient way to predict error performance from noise and signal-level characteristics.

I.4.3 Optical signal-to-noise ratio (OSNR)

Optical Signal-to-Noise Ratio parameter quantifies the quality of the optical signal by comparing its power to that of the noise within a specific optical bandwidth. It is defined as:

$$\text{OSNR} = \frac{P_{\text{signal}}}{\text{Noise Power Density}}$$

In practical terms, OSNR is usually measured in decibels (dB) using an optical spectrum analyzer (OSA) with a defined resolution bandwidth. In optical networks especially those with inline optical amplifiers; the dominant noise is often amplified spontaneous emission (ASE).

Thus, OSNR becomes crucial in determining whether the optical signal can be reliably detected at the receiver, independent of the actual signal power. [21]

I.4.4 OSNR penalty

OSNR penalty estimates the degradation in an optical communication system by measuring the additional OSNR needed to get a specified pre-forward error correction (pre-FEC) bit error rate relative to an optimal, back-to-back reference scenario. It signifies the extent to which the quality of the optical link is degraded by different impairments, including nonlinear effects, channel crosstalk, and other transmission disturbances, leading to increased noise at the receiver.

$$\text{OSNR Penalty (dB)} = \text{OSNR}_{\text{with impairment}} - \text{OSNR}_{\text{reference}}$$

Where $\text{OSNR}_{\text{reference}}$ is the OSNR needed without the impairment. This penalty offers insight into the erosion of overall system performance and is utilized for monitoring and managing link quality in coherent optical networks. [22]

I.4.5 Transmission reach

Transmission reach refers to the maximum distance an optical signal can travel while maintaining acceptable performance (e.g., target BER and signal quality), limited by impairments like fiber loss, chromatic dispersion, and amplifier noise. A key performance metric is the product of transmission distance and data capacity (expressed in Gb/s*km), where higher capacity or longer distance enhances reach, but practical limits arise from physical fiber impairments. [23]

$$\text{Transmission Reach} = \text{Transmission Distance} \times \text{Capacity}$$

I.5 Conclusion

In summary, coherent optical WDM systems signify a transformative advancement in optical communications, merging great spectral efficiency with increased transmission distance through the synergistic integration of coherence detection, sophisticated modulation formats, and digital signal processing. This chapter has clarified the essential principles regulating these systems, illustrating how their power to mitigate linear and nonlinear impairments using DSP facilitates unparalleled data capacity in long-haul networks. The technological breakthroughs outlined above, including advanced modulation techniques, wavelength-multiplexing structures, and adaptive compensation algorithms, collectively constitute the foundation of contemporary high-speed optical infrastructure. As we go towards terabit-per-second transmission capacities, these coherent systems persist in redefining the limits of optical networking, providing scalable solutions for future bandwidth requirements while preserving strong signal integrity over transoceanic distances. This chapter's ideas establish a crucial basis for comprehending both present applications and forthcoming advancements in this swiftly developing domain.

Chapter II:
Nyquist-WDM: principles and advantages

II.1 Introduction

The escalating requirement for high-speed data transmission in contemporary communication networks has propelled the advancement of optical transmission technologies. Wavelength Division Multiplexing (WDM) is one of the most successful ways for augmenting transmission capacity, since it allows for the concurrent transmission of many data channels over a single optical fiber by designating each channel a distinct wavelength. Conventional Dense Wavelength Division Multiplexing (DWDM) systems have markedly increased bandwidth utilization; nonetheless, they encounter constraints regarding spectral efficiency and vulnerability to inter-channel interference when channel spacing diminishes.

To address these issues, sophisticated methods like Nyquist-WDM have been developed. Nyquist-WDM utilizes Nyquist pulse shaping concepts to enhance spectral efficiency by minimizing inter-symbol and inter-channel interference.

This chapter examines the fundamentals of wavelength division multiplexing and Nyquist-WDM systems, contrasting their principles, components, and constraints. Moreover, it emphasizes the benefits of Nyquist-WDM in attaining higher channel density, enhanced spectral efficiency, and compatibility with sophisticated modulation schemes. A mathematical framework is provided to simulate nonlinear effects and inter-channel crosstalk, facilitating a thorough comprehension of the performance trade-offs between traditional and spectrally efficient WDM approaches.

II.2 Transmission techniques: methods to enhance the transmitted bit rate

Optical fibers provide an extensive bandwidth of around 15 THz at 1.55 µm, theoretically facilitating exceptionally high transmission speeds. This potential is fundamental in light of the increasing needs for information today. Nonetheless, restrictions in electronic processing impede the direct utilization of this bandwidth. Multiplexing techniques are utilized to close this gap. [24]

Multiplexing fundamentally facilitates the efficient utilization of a singular communication channel by amalgamating numerous independent signals into one intricate transmission. This optimizes bandwidth usage and minimizes the necessity for several physical connections, hence improving network performance. The fundamental premise entails consolidating 'N' signals, each possessing a data rate 'D', to attain a cumulative data rate of 'N*D', beyond the capabilities of existing single-signal electronic processing. At the receiving end, demultiplexing segregates the component signals for processing. [25]

Multiplexing preserves signal integrity by creating separation between signals through temporal, spatial, or frequency disparities. A notable instance of this is wavelength division multiplexing.

II.3 Wavelength Division Multiplexing

II.3.1 Principles of WDM

Wavelength Division Multiplexing involves transmitting N optical carriers, each at a different wavelength, through a single optical fiber, with each carrier carrying a data rate of D_b. Instead of dividing the time axis into intervals for each user, the bandwidth is divided, and each sub-band is allocated to a specific channel. This method allows multiple transmissions to occur simultaneously, each operating on a distinct frequency band. This technique is also referred to as Frequency Division Multiplexing (FDM).

The distinction between WDM and FDM in optical communications is primarily based on channel spacing: WDM is typically used when the wavelength separation between channels is relatively large (greater than 1 nm), while FDM is used for narrower channel spacing. [24]

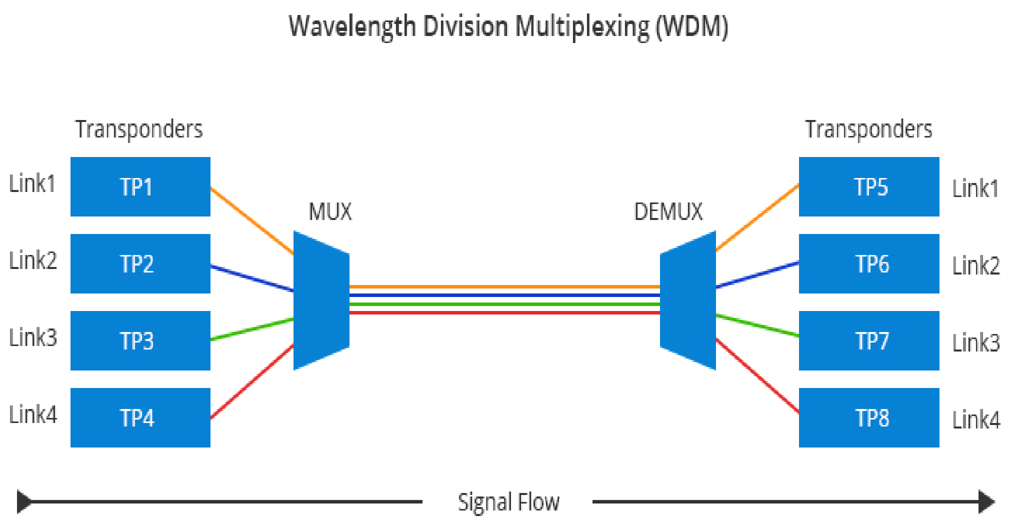


Figure II.1: Principle of a WDM system, mux (multiplexer), demux (demultiplexer).

II.3.2 Varied modalities of wavelength division multiplexing technology

This section emphasizes the most frequently utilized components in optical transmission applications:

II.3.2.a Coarse Wavelength Division Multiplexing (CWDM)

Coarse Wavelength Division Multiplexing is an efficient solution for short-distance communication, especially in fiber optic networks with spans under 50 km that do not need signal regeneration or optical amplification. These systems employ 2.5 Gbps lasers and can combine up to 18 wavelengths, delivering a total capacity of 45 Gbps per fiber. The optical transceiver, which combine both the transmitting laser and receiving detector, simplifies the setup. Since CWDM uses optical multiplexers and demultiplexers tailored to specific wavelengths without stringent wavelength control, it is more cost-effective than Dense WDM (DWDM). Furthermore, CWDM follows the ITU-T G.694.2 standard, featuring a channel spacing of 20 nm (or 2500 GHz). [25]

II.3.2.b Dense Wavelength Division Multiplexing (DWDM)

Dense Wavelength Division Multiplexing is a high-capacity optical technology where channels are spaced less than 1.6 nm (200 GHz) apart, enabling the transmission of numerous wavelengths over a single fiber. Modern systems can support up to 32 channels in the C-band and 128 channels when combining the C, S, and L bands. Due to increasing demand for bandwidth, DWDM has seen major improvements in reliability, speed, and performance, making it ideal for both short- and long-haul applications, including metro and core networks with heavy traffic loads.

It typically use 10 Gbps lasers, but their transceivers require more power and generate more heat than CWDM systems, often needing active cooling. While DWDM delivers much higher capacity, it also involves more complex and expensive equipment. Channel spacings can be as narrow as 12.5 GHz, allowing over 300 channels to travel thousands of kilometers with periodic amplification. As per the ITU-T G.694.1 standard, DWDM operates with spacings of 50 or 100 GHz, centered at 193.1 THz, and primarily functions in the C-band (1530–1565 nm) or L-band (1565–1625 nm).

Compared to CWDM, DWDM offers far finer wavelength granularity (typically 100 GHz spacing), making it the preferred choice for ultra-high-capacity networks [26].

Table II.1 below provides a comparison between the two types of multiplexing technologies (CWDM and DWDM). The total transmission capacity for CWDM technology is 40 Gbps, whereas for DWDM technology, it can reach up to 1000 Gbps. This highlights a significant difference between the two multiplexing techniques.

Feature	DWDM (Dense Wavelength Division Multiplexing)	CWDM (Coarse Wavelength Division Multiplexing)
Channel Spacing	0.2 nm – 1.6 nm (12.5 GHz – 200 GHz)	20 nm (2500 GHz)
Number of Channels	Up to 32 in C-band, up to 128 in C, S, and L bands	Up to 18 wavelengths
Wavelength Range	1530 nm – 1625 nm (C-band & L-band)	1470 nm – 1610 nm
Data Rates	10 Gbps – 400 Gbps	Up to 2.5 Gbps per channel

Maximum Capacity	Multiple terabits per fiber	Up to 45 Gbps per fiber
Laser Type	Cooled, high-precision lasers	Uncooled, lower-cost lasers
Distance Coverage	Up to thousands of km with amplification	Up to 50 km (no amplification)
Amplification Requirement	Requires EDFA for long-haul	Not needed
System Cost	Higher due to tight wavelength control and amplification	Lower due to relaxed wavelength control
ITU-T Standard	G.694.1	G.694.2
Transceiver Complexity	Complex, high-performance	Simple, cost-effective
Power Consumption	Higher, due to cooled lasers and amplifiers	Lower, due to uncooled lasers
Interference and Filtering	Requires precise filtering due to dense channels	Less strict filtering required
Primary Use Cases	Long-haul, core, and high-capacity data networks	Short-distance metro and access networks

Table II.1: Comparison between CWDM and DWDM.

Figure II.2 compares two wavelength division-multiplexing technologies. The diagram highlights the fundamental trade-off: CWDM offers affordability and simplicity at lower capacity, while DWDM provides high performance at greater cost and complexity [27].

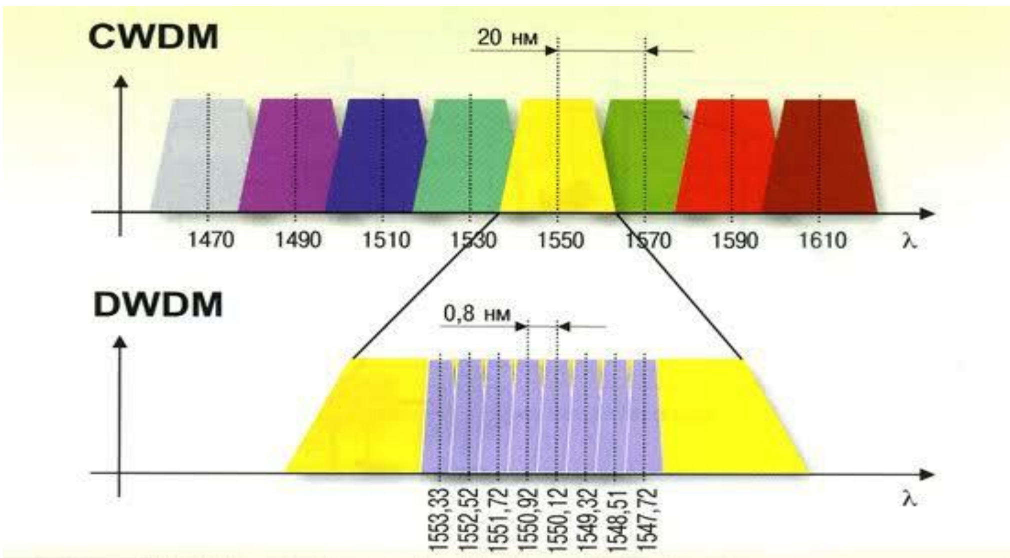


Figure II.2: Distinction between CWDM and DWDM.

II.3.3 WDM Component

II.3.3.a Multiplexers/Demultiplexers

Arrayed Waveguide Gratings (AWGs) are used for multiplexing and demultiplexing, particularly in DWDM systems with a high number of channels.

The optical signal processing in Figure II.3 begins with an input fiber delivering light to a coupler, which splits the signal into arrayed waveguides. These waveguides introduce distinct phase shifts to each wavelength. A second coupler then separates the wavelengths ($\lambda^1, \lambda^2, \lambda^3$, λ^4), directing them to individual output fibers. This configuration employs arrayed waveguide gratings to achieve accurate wavelength division and channel allocation.

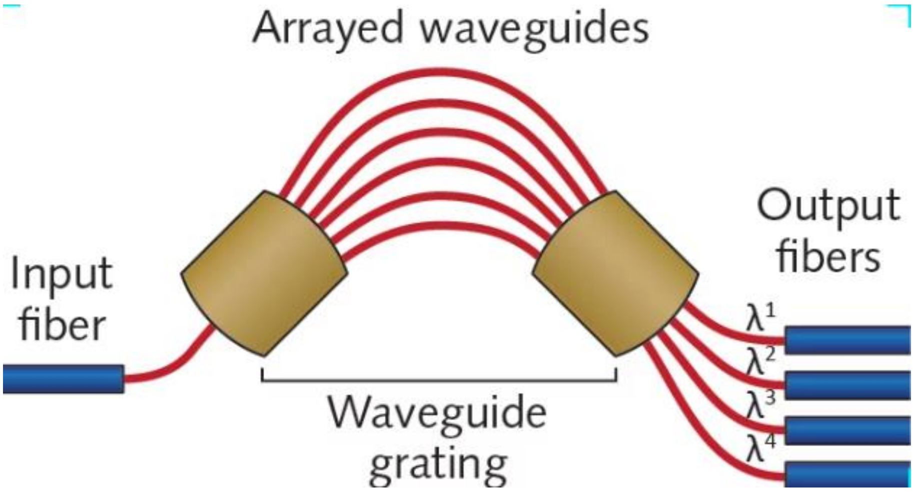


Figure II.3: An array waveguide grating.

II.4 Nyquist-WDM system

Conventional DWDM systems, while significantly expanding optical fiber capacity, are constrained by inherent spectral inefficiencies. Fixed channel spacing, set by the ITU grid, requires large gaps between channels to reduce interference, which leads to wasted optical bandwidth. As per-channel data rates escalate, these guard bands become a critical bottleneck, impeding further capacity scaling. Additionally, problems like chromatic dispersion and nonlinear interactions limit how efficiently data can be transmitted and how far it can travel.

To address these shortcomings and fully exploit the potential of optical fiber, advanced spectrally efficient techniques are imperative. This necessity has spurred the development of sophisticated modulation formats and digital signal processing methodologies, culminating in the exploration of Nyquist-WDM.

Nyquist-WDM fundamentally optimizes spectral efficiency by aligning channel bandwidth with the symbol rate, adhering to the Nyquist-Shannon sampling theorem, thereby minimizing inter-channel interference and enabling tighter channel packing. This paradigm shift has facilitated the transition from traditional, spectrally sparse WDM systems to high-density super-channels, which are now indispensable for meeting the exponential growth in optical fiber communication demands.

Since the mid-2010s, commercial Nyquist-WDM systems have demonstrated per-channel data rates of 100 Gb/s, with experimental setups achieving 200 Gb/s. The adoption of super-channels, which aggregate multiple optical signals into a spectrally efficient composite signal, circumvents electronic processing limitations by leveraging optical parallelism. This approach not only enhances spectral efficiency but also establishes a foundation for ultra-high-speed optical networks capable of terabit-per-second data transmission.

Table II.2 provides a classification of WDM systems based on the channel spacing ratio $(\Delta f/B)$ and their respective application domains. It encompasses Coarse WDM, traditional WDM, and high-density DWDM, alongside advanced techniques such as Quasi-Nyquist WDM, Nyquist-WDM, and Super-Nyquist WDM, which demonstrably improve spectral efficiency through reduced channel spacing. This classification underscores the evolution of WDM technology towards greater spectral efficiency and higher capacity to meet the demands of modern communication networks. [28]

Definition	**Condition (Δf/B)**	**Example**
Coarse WDM	> 50	10 Gb/s en 20 nm
WDM	> 5	10 Gb/s en 100 GHz
DWDM	$1.2 < \Delta f/B \leq 5$	28-Gbaud PDM-QPSK en 50 GHz
'Quasi-Nyquist' WDM	$1 < \Delta f/B \leq 1.2$	28-Gbaud PDM- 16QAM en 33 GHz
'Nyquist' WDM	$\Delta f/B = 1$	28-Gbaud PDM-QPSK en 28 GHz
'super-Nyquist' WDM	$\Delta f/B < 1$	28-Gbaud PDM-QPSK en 25 GHz

Table II.2: Definitions of different WDM classes.

The key concept behind Nyquist-WDM is the use of Nyquist pulses, which have an ideal rectangular spectrum, allowing channels to be packed more closely without causing crosstalk. These pulses play a central role in achieving high spectral efficiency and minimizing inter-symbol interference in modern optical communication systems. Their generation can be realized through optical filtering techniques or digital pulse shaping before optical modulation, often combining both for optimal performance. Common pulse shaping techniques include raised cosine and sinc filtering, which ensure minimal bandwidth usage while maintaining data integrity. [29] [30]

II.4.1 The Nyquist criterion

As we mentioned before, the foundational principle of Nyquist-WDM is rooted in the Nyquist-Shannon sampling theorem, a cornerstone of information theory. This theorem establishes the minimum sampling rate required to reconstruct a band-limited signal perfectly. In the realm of optical communication, this equation translates to a critical relationship between the symbol rate and the channel bandwidth.

Specifically, the theorem dictates that a signal with a maximum frequency component 'B' can be perfectly reconstructed if sampled at a rate of at least '2B'. In Nyquist-WDM, this principle is applied to the spectral domain. Instead of time-domain sampling, we are concerned with the spectral occupancy of optical signals. The goal is to reduce the amount of spectral bandwidth given to each channel so that it exactly fits its symbol rate, which helps us reach the best possible use of spectral efficiency.

Conventional WDM systems add extra space between channels to stop interference, which goes beyond the minimum bandwidth needed according to the Nyquist criterion. These guard bands help keep the signals clear in less efficient systems, but they take up a lot of space on the fiber, reducing its total capacity. Nyquist-WDM, on the other hand, uses advanced methods to shape signals, like sinc pulse shaping or other modulation formats, to keep the space each channel uses as small as possible. This method allows channels to be packed densely, with minimal or no guard bands, significantly enhancing spectral efficiency.

The raised cosine (RC) filter, shown in Figure II.4, is an important method for shaping signals that satisfies the strict frequency needs for Nyquist-WDM systems. By carefully adjusting the roll-off factor (α), the RC filter prevents any overlap between symbols at the sampling times while making the best use of available bandwidth. In Nyquist-WDM, this approach synchronizes the channel bandwidth precisely with the symbol rate, enabling the transmission of higher data rates within the same optical spectrum. This method not only maximizes the capacity of existing fiber infrastructure but also paves the way for future ultra-high-speed advancements. However, to reach this best performance, careful signal shaping and advanced digital signal processing techniques are needed to tackle ongoing issues like inter-carrier interference and timing jitter. The RC filter can adjust from a perfect "brick-wall" response (α=0) to gentler roll-offs (α=1), showing its ability to balance efficient use of the spectrum with reliable performance, which is essential for today's optical and wireless communication systems.

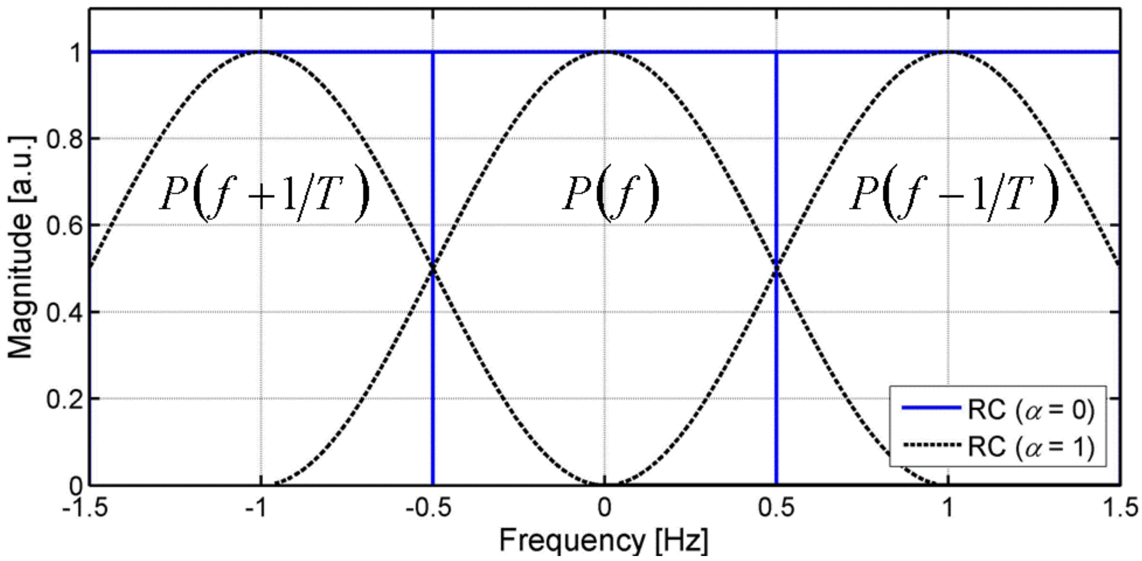


Figure II.4: Representation in the frequency domain of Nyquist criterion, symbol duration T

The Figure II.5 depicts the frequency response *H(f)* of a raised-cosine filter for different roll-off factors (β), illustrating how β influences the filter's transition band. The plot highlights this trade-off: smaller β maximizes bandwidth efficiency, whereas larger β improves signal integrity in dispersive channels.

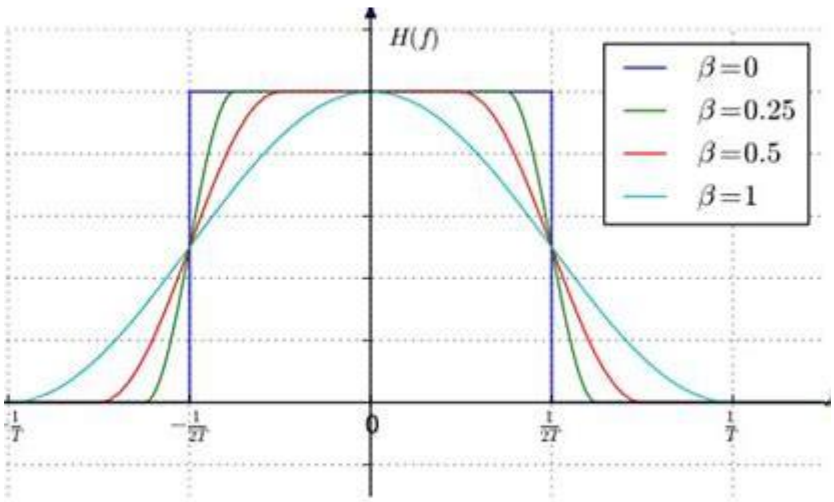


Figure II.5: Frequency response of raised-cosine filter with various roll-off factors.

II.4.2 Spectral efficiency of Nyquist-WDM

Nyquist-WDM is a transmission strategy that enhances spectral efficiency by using tight pulse shaping and minimizing guard bands. It restricts the broadcast signal's spectrum to minimize ISI, allowing channels to be packed more closely than conventional DWDM systems. The following sections delve into these challenges, exploring strategies to balance SE.

II.4.2.a Minimizing inter-symbol interference

Inter-symbol interference occurs when the tail of one pulse overlaps with consecutive pulses, causing energy from one symbol to leak into another's time interval. The finite bandwidth of communication channels, channel-induced distortions, and limitations in pulse shaping exacerbate this interference, potentially leading to detection errors.

To mitigate ISI, Nyquist-WDM systems employ pulse-shaping techniques based on the Nyquist criterion. Ideally, pulses would have a sharp peak with zero values at all other sampling instants. In practice, however, pulses have “tails” that must be minimized through advanced filtering and design strategies. By ensuring that each symbol’s energy is confined to its designated time slot, the system significantly reduces detection failures and enhances overall performance. [31] [32]

II.4.2.b Minimization of inter-channel interference

Inter-Channel Interference refers to the undesirable interference among neighboring optical channels. Conventional Dense WDM systems often require guard bands between channels to mitigate this effect. In contrast, Nyquist-WDM utilizes sophisticated pulse shaping often with sinc or cosine–shaped pulses that fulfills the Nyquist first criterion (ensuring zero ISI at the sampling instants). This technique not only minimizes ISI but also reduces leakage into adjacent channels, thereby decreasing ICI and further improving spectral efficiency. [33]

II.4.2.c Dispersion compensation

In Nyquist-WDM systems, precise dispersion management is critical to maintaining signal integrity and maximizing spectral efficiency. After an optical band-pass filter extracts the desired spectral components, residual chirp may persist in the signal, potentially distorting the temporal pulse shape. To address this, a carefully calibrated segment of standard single-mode fiber (SSMF) is used to introduce a controlled amount of chromatic dispersion, which compensates for the nonlinear phase changes (chirp) introduced during modulation. This compensation linearizes the phase of the optical signal, reshaping the pulse's temporal profile to more closely approximate an ideal sinc function—a crucial requirement for minimizing inter-symbol interference (ISI) in tightly spaced Nyquist-WDM channels. By effectively mitigating chirp-induced distortions, this approach not only reduces ISI but also enhances overall system performance, enabling higher data rates and improved spectral efficiency.

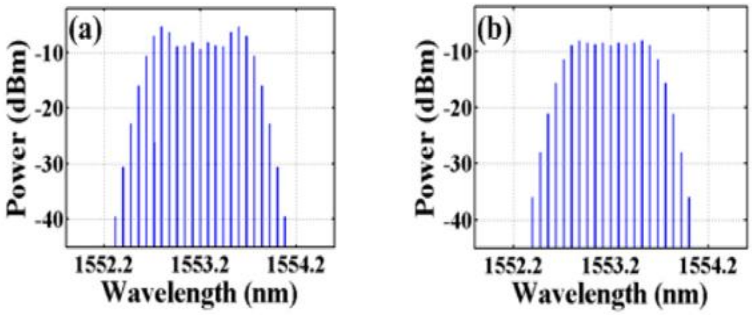


Figure II.6: Impact of dispersion on optical signal spectrum.

Figure II.6 illustrates two optical spectra, designated (a) and (b), depicting power distribution in dBm as a function of wavelength in nanometers (nm). Both spectra display a multi-carrier configuration, signifying the existence of several optical channels or sub-carriers centered at a wavelength of roughly 1553.2 nm.

The spectrum in scenario a (without dispersion) exhibits a very uniform power distribution in the middle channels, with power diminishing progressively towards the peripheries of the measured wavelength range (about 1552.4 nm and 1554.0 nm). Spectrum b, characterized by -20 ps/nm dispersion, exhibits a somewhat distinct power distribution throughout the channels. Although centered at 1553.2 nm, the inner channels may exhibit a little different relative power in comparison to the peripheral channels as observed in spectrum (a). This spectrum is broadened, illustrating the influence of dispersion on spectral energy distribution.

The impact of dispersion compensation is clearly illustrated in Figure II.7, which shows how optimized dispersion management can sharpen spectral peaks and minimize power broadening.

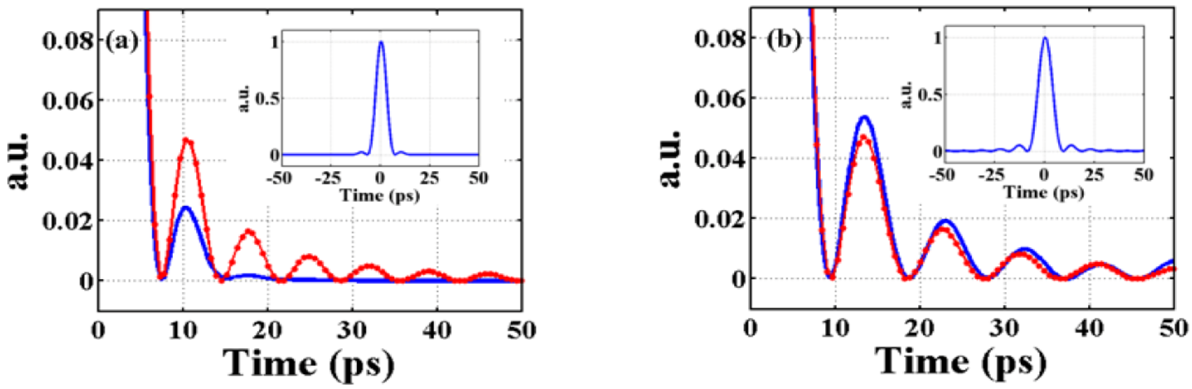


Figure II.7: Temporal waveform after dispersion compensation with and without optical filtering.

- In subfigure (a), the blue solid line represents the temporal waveform without optical filtering, while the red dotted line is the fitted sinc function curve. It is evident that without optical filtering, the waveform deviates from the ideal sinc shape, showing unwanted ripples and side lobes.
- In subfigure (b), the application of optical filtering refines the waveform, aligning it more closely with the ideal sinc shape, as indicated by the reduced side lobes and improved temporal confinement. This demonstrates the importance of optical filtering in Nyquist pulse generation, ensuring better spectral confinement and minimizing inter-symbol interference. [34] [35]

This technique highlights the importance of adaptive dispersion control in high-speed optical communication systems, where even minor phase distortions can significantly degrade performance. Future advancements may incorporate tunable dispersion-compensating fibers or dynamic feedback systems to further refine this process under varying transmission conditions.

II.4.2.d Advanced modulation Formats

To meet the growing need for higher data rates and improved spectral efficiency, advanced modulation techniques have become indispensable in modern optical communication systems. These methods pack more bits into each transmitted symbol, significantly increasing the data-carrying capacity within the same channel bandwidth. Among the most widely adopted schemes are:

Quadrature Phase Shift Keying (QPSK) modulates the carrier phase to assume one of four possible values normally spaced 90° apart, enabling the transfer of 2 bits per symbol. This approach provides an equitable trade-off between spectral efficiency and noise resistance. 16-Quadrature Amplitude Modulation (16-QAM) conveys 4 bits each symbol, hence doubling the capacity relative to QPSK. When integrated with coherent detection methods and Nyquist pulse shaping, 16-QAM can provide exceptionally high data throughput while preserving satisfactory error performance.

Advanced modulation approaches, bolstered by robust digital signal processing technologies that mitigate challenges such as chromatic dispersion and fiber nonlinearities, are essential for improving the spectral efficiency of Nyquist-WDM systems.

II.4.2.e Trade-offs Between spectral efficiency and system complexity

Achieving high spectral efficiency in Nyquist-WDM systems is not without cost. The benefits of close channel spacing and tight spectral confinement come at the price of increased system complexity-especially in the digital signal processing required for pulse shaping, equalization, and nonlinearity compensation.

This Figure II.8 shows how the dynamic energy consumption increases with the number of filter taps, emphasizing the trade-off between filter performance (and therefore spectral efficiency) and hardware complexity/energy efficiency.

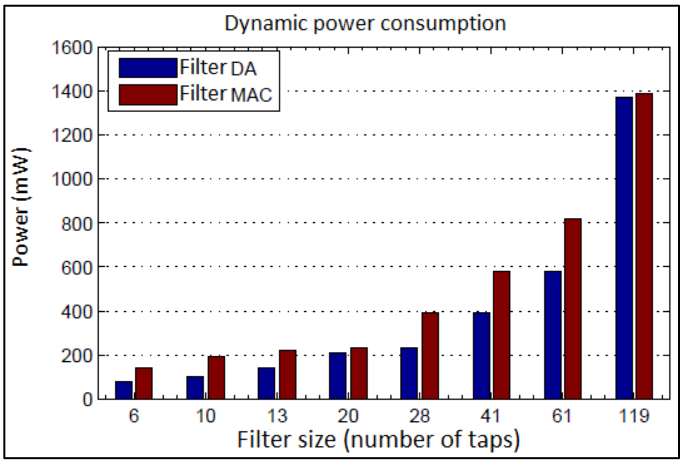


Figure II.8: Consumption of MAC and DA FIR filters for different taps.

This figure illustrates the dynamic power consumption of two types of FIR filters which are the multiply-accumulate (MAC) and distributed arithmetic (DA) as a function of the filter size (number of taps). It highlights how increasing filter complexity directly affects the power consumption, balancing spectral efficiency with system complexity.

Nyquist-WDM systems require advanced pulse shaping and filtering techniques to achieve optimal spectral efficiency, making the computational load of digital filters a critical element in overall system performance. The figure emphasizes the trade-offs involved in choosing a higher number of filter taps, improving pulse shaping but also leading to higher power consumption.

The use of advanced equalization algorithms, such as blind equalization, decision-directed least-mean-square (DD-LMS), and Volterra series-based nonlinear equalizers, significantly increases computational complexity. Similarly, the adoption of advanced modulation formats like 16-QAM and coherent detection schemes further escalates system complexity. These formats require precise carrier phase recovery and more robust DSP algorithms, adding to the processing burden.

Although new modulation formats enhance spectral efficiency, they also demand higher signal-to-noise ratios (SNR) and place a greater strain on the receiver's DSP. This added complexity is reflected in both increased processing requirements and power consumption. Therefore, system design requires a careful trade-off between the advantages of higher data rates and the challenges posed by hardware implementation. [33] [36] [37]

II.5 Comparison of Nyquist-WDM with conventional DWDM

This comparison of DWDM and Nyquist-WDM reveals their key differences in channel spacing, spectral efficiency, inter-channel interference management, and overall system complexity as provide in Table II.3.

Parameter	DWDM	WDM Nyquist
Technology Type / Definition	A multiplexing technique that packs many channels with very narrow spacing; used for high-capacity, long-haul transmission systems.	A variant of WDM that employs Nyquist pulse shaping to minimize inter-channel interference (ICI) and maximize spectral efficiency.
Channel Spacing	Typically, between 0.2 nm and 0.8 nm, which allows for a much higher number of channels within the same spectral band.	Channel spacing is reduced to nearly the theoretical Nyquist limit (often on the order of the symbol rate), allowing extremely dense channel packing.
Number of Channels	Can support up to 96 channels (in the C-band) and theoretically up to 160 channels with tighter spacing.	Can potentially accommodate an even larger number of channels due to minimized guard bands, with capacity ultimately limited by the available spectrum.
Wavelength Range	Primarily operates in the C-band (approximately 1530–1565 nm) and sometimes in the L-band for extended capacity.	Use the same wavelength bands as DWDM (e.g., C-band) but leverages advanced modulation schemes for optimal spectral utilization.
Spectral Efficiency	Higher spectral efficiency compared to CWDM; however, guard bands are still required to prevent ICI between closely spaced channels.	Highest spectral efficiency among the three by minimizing guard bands and ICI through Nyquist pulse shaping, allowing channels to be packed more tightly.
Transmission Distance & Capacity	Capable of long-haul transmission (typically around 80 km or more at 10 Gb/s, extendable with optical amplifiers) thanks to precise components.	Designed for high-capacity systems, enabling long-distance transmission with minimized interference, often employed in advanced data center and backbone networks.
Equipment Complexity & Cost	Requires high-precision lasers, filters, and temperature-controlled components, making it more complex and expensive.	Involves advanced digital signal processing and precise filtering techniques; although initially more

Parameter	DWDM	WDM Nyquist
		complex and costly, it offers significant performance gains.
Inter-Channel Interference (ICI)	ICI can be a concern if channels are too close; therefore, guard bands are used to mitigate interference.	Nyquist pulse shaping minimizes ICI dramatically, permitting channels to be placed closer together without degrading performance.
Applications	Long-haul and core transport networks, supporting high data rates and extensive channel counts in telecom and data backbones.	Targeted for next-generation high-capacity systems, including data centers and advanced optical networks.
Technology Maturity	A very mature and widely deployed technology across global telecom networks.	Emerging and evolving; currently a focus of research and development aimed at overcoming spectral limitations in future optical communication systems.

Table II.3: Comparative analysis of DWDM and Nyquist-WDM technologies.

The following figure II.9 illustrates how channel spacing relative to the symbol rate varies across four multiplexing schemes: Standard WDM, Ideal Nyquist-WDM, Quasi-Nyquist-WDM, and Super-Nyquist-WDM.

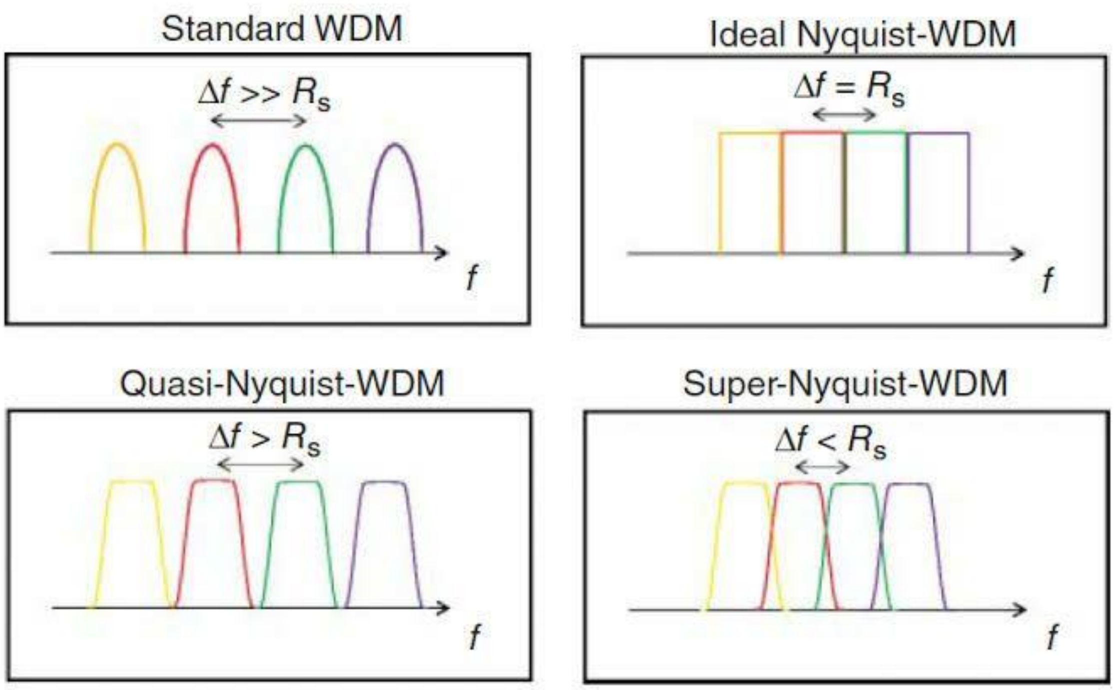


Figure II.9: Spectral efficiency comparison: standard WDM vs. Nyquist-WDM variants.

It highlights the trade-off between spectral efficiency and system complexity, showing how closer channel packing (as in Nyquist-based approaches) increases capacity but requires more sophisticated filtering and digital signal processing to handle interference.

- **Standard WDM (Top Left)**
  - ✓ The channel spacing Δf is much larger than the symbol rate R_s.
  - ✓ Each channel is separated by a wide guard band, which minimizes interference but reduces spectral efficiency.
  - ✓ This approach is simpler to implement but does not fully utilize the available spectrum.
  - ✓ Standard WDM uses wide spacing, which is easier to implement but not very efficient in terms of spectrum usage.
- **Ideal Nyquist-WDM (Top Right)**
  - ✓ The channel spacing Δf is exactly equal to the symbol rate R_s.
  - ✓ By using Nyquist pulse shaping, each channel's spectrum can fit snugly next to the others without overlapping.
  - ✓ This achieves maximum spectral efficiency for a given symbol rate and minimizes inter-channel interference (ICI).
  - ✓ Nyquist-WDM aims to perfectly pack channels with no guard bands, achieving optimal efficiency if ideal pulse shaping is used.
- **Quasi-Nyquist-WDM (Bottom Left)**
  - ✓ The channel spacing Δf is slightly larger than the symbol rate R_s.
  - ✓ There is a small guard band to account for non-ideal filters and real-world impairments.
  - ✓ While it's not as efficient as the ideal case, it reduces complexity and offers better performance in practical systems.
  - ✓ Quasi-Nyquist-WDM slightly relaxes the ideal spacing to accommodate real-world hardware limitations.
- **Super-Nyquist-WDM (Bottom Right)**
  - ✓ The channel spacing Δf is less than the symbol rate R_s.
  - ✓ Channels overlap in the frequency domain, requiring advanced digital signal processing to separate them and mitigate interference.
  - ✓ Super-Nyquist-WDM goes beyond the Nyquist limit in terms of spacing, increasing capacity further but demanding more sophisticated interference cancellation methods. [38]

Nyquist-WDM surpasses DWDM in spectral efficiency by eliminating guard bands through advanced pulse shaping, enabling denser channel packing. In addition, Nyquist-WDM leverages digital signal processing, reducing hardware complexity. This makes Nyquist-WDM ideal for high-speed metro and backbone networks, offering higher data rates and improved spectral utilization.

II.6 Mathematical modeling of channel impairments

The implementation of wavelength division multiplexing and optical amplification to augment information capacity and/or transmission distance in optical fiber networks has resulted in considerable propagation impairments caused by fiber nonlinearity. Key nonlinear phenomena contributing to interchannel crosstalk in WDM systems include cross-phase modulation (XPM) and four-wave mixing (FWM). To attain elevated data rates and an enhanced signal-to-noise ratio, the system must be refined to alleviate distortions and nonlinear phenomena such as cross-phase modulation and four-wave mixing.

II.6.1 Cross-Phase Modulation (XPM)

Cross-Phase Modulation occurs when the leading edge of an optical pulse shifts toward longer wavelengths due to nonlinear effects. This phenomenon interacts with self-phase modulation (SPM), impacting both transmission distance and overall system performance The electric field can be expressed in a way that separates its rapidly varying components as follows:

$$E(r,t) = \frac{1}{2}\hat{x}[E_1 \exp(-i\omega_1 t) + E_2 \exp(-i\omega_2 t)] \quad \text{(II.1)}$$

Here, $\hat{\mathbf{x}}$ represents the polarization unit vector, $\boldsymbol{\omega_1}$ and $\boldsymbol{\omega_2}$ are the carrier frequencies of the two pulses, and their corresponding amplitudes, $\mathbf{E_1}$ and $\mathbf{E_2}$, are assumed to vary slowly over time relative to an optical period. This assumption is equivalent to stating that the spectral width of each pulse satisfies the condition $\Delta\omega_j << \omega_j$ (where $j = 1, 2$), which holds true for pulse widths greater than **0.1 ps**. The evolution of the slowly varying amplitudes E_1 and E_2 is described by the following wave equation:

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P_L}{\partial t^2} + \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2} \quad \text{(II.2)}$$

To understand the origin of Cross-Phase Modulation, we substitute Equation (II.1) into the following expression for the nonlinear component of the induced polarization:

$$P_{NL}(r,t) = \varepsilon_0 \chi^{(3)} \vdots E(r,t)E(r,t)E(r,t) \quad \text{(II.3)}$$

Thus, we obtain the following expression for the nonlinear polarization:

$$P_{NL}(r,t) = \frac{1}{2}\hat{x}\begin{bmatrix} P_{NL}(\omega_1)\exp(-i\omega_1 t) + \\ P_{NL}(\omega_2)\exp(-i\omega_2 t) + \\ P_{NL}(2\omega_1 - \omega_2)\exp[-i(2\omega_1 - \omega_2)t] + \\ P_{NL}(2\omega_2 - \omega_1)\exp[-i(2\omega_2 - \omega_1)t] \end{bmatrix} \quad \text{(II.4)}$$

Where the four terms depend on E_1 and E_2 as:

$$\begin{aligned} P_{NL}(\omega_1) &= \chi_{eff}(|E_1|^2 + 2|E_2|^2)E_1 \\ P_{NL}(\omega_2) &= \chi_{eff}(|E_2|^2 + 2|E_1|^2)E_2 \\ P_{NL}(2\omega_1 - \omega_2) &= \chi_{eff}\, E_1^2\, E_2^* \\ P_{NL}(2\omega_2 - \omega_1) &= \chi_{eff}\, E_2^2\, E_1^* \end{aligned} \quad \text{(II.5)}$$

With $\chi_{eff} = (3\varepsilon_0/4)\chi^{(3)}_{xxxx}$ acting as an effective nonlinear parameter.

The induced nonlinear polarization in Equation (II.2) includes terms that oscillate at the new frequencies **$2\omega_1 - \omega_2$** and **$2\omega_2 - \omega_1$**. The remaining two terms contribute to the nonlinear refractive index. This can be observed by expressing $P_{NL}(\omega_j)$ in the following form (where j = 1, 2):

$$P_{NL}(\omega_j) = \varepsilon_0 \varepsilon_j^{NL} E_j \quad \text{(II.6)}$$

By combining it with the linear component, the total induced polarization can be expressed as:

$$P(\omega_j) = \varepsilon_0 \varepsilon_j E_j \quad \text{(II.7)}$$

Where $\varepsilon_j = \varepsilon_j^L + \varepsilon_j^{NL} = (n_j^L + \Delta n_j)^2$

The linear component of the refractive index is denoted as n_j^L, while Δn_j represents the modification caused by third-order nonlinear effects. Assuming Δn_j is significantly smaller than n_j^L (i.e., $\Delta n_j \ll n_j^L$), the nonlinear contribution to the refractive index can be expressed as follows (where **j = 1, 2**):

$$\Delta n_j \approx \varepsilon_j^{NL}/2n_j \approx n_2(|E_j|^2 + 2|E_{3j}|^2) \quad \text{(II.8)}$$

Where ${n^L}_1 \approx {n^L}_2 = n$ has been assumed.

Equation (II.8) clearly demonstrates that the refractive index encountered by an optical field in an optical fiber is affected by its own intensity as well as the intensities of other co-propagating fields. As the optical field propagates through the fiber, it acquires a nonlinear phase shift contingent upon its intensity.

$$\varphi_j^{NL}(z) = (\omega_j/c)\Delta n_j z = n_2(\omega_j/c)(|E_j|^2 + 2|E_{3j}|^2)z \quad \text{(II.9)}$$

Here, j=1 or 2. The first term in the equation corresponds to self-phase modulation, while the second term arises from the phase modulation of one wave by the other co-propagating wave, representing cross-phase modulation. The factor of 2 on the right-hand side of Equation (II.9) indicates that XPM is twice as effective as SPM for the same intensity.

II.6.2 Mathematical model XPM induced Crosstalk

Consider two optical waves with the same polarization propagating in a single-mode fiber, as previously described. Let $A_k(z,t)$ represent the slowly varying complex field envelope of each wave, normalized such that $|A|^2=P_k$, where P_k is the power of the wave. The coupled equations governing cross-phase modulation under the slowly varying envelope approximation can be expressed as follows:

$$\frac{\partial A_1}{\partial z}+\frac{1}{V_{g1}}\frac{\partial A_1}{\partial z}=\left(i2\gamma P_2-\frac{\alpha}{2}\right)A_1$$

$$\frac{\partial A_2}{\partial z}+\frac{1}{V_{g2}}\frac{\partial A_2}{\partial z}=(i2\gamma P_1-\alpha/2)A_2 \quad \text{(II.10)}$$

Under the same initial conditions used at the fiber input, the resulting equations are derived as follows:

$$A_2(z,\tau_2)=A_2(0,\tau_2)\exp(-\alpha z/2)\times\exp[-2y\int_1^z P_1(0,\tau_2+d_{21}z)dz \quad \text{(II.11)}$$

Where, γ is nonlinear coefficient.

At this point, the crosstalk is entirely contained within the phase term 2ϕ, where ϕ represents the nonlinear phase shift induced by the interaction between the co-propagating waves. This phase shift is given by:

$$\varphi_2=-2\gamma\int_0^z P_1(0,\tau_2+d_{21}z)e^{-\alpha z}dz \quad \text{(II.12)}$$

GVD converts phase modulation to intensity modulation, as expressed by:

$$\frac{dP_2(z,\tau_2)}{dz}=\beta_2 P_2(0,\tau_2)e^{-\alpha z}\frac{d^2\phi_2(z,\tau_2)}{d\tau_2^2} \quad \text{(II.13)}$$

Here, $\beta=d^2\beta_2/d\omega^2$, where β_2 is the phase constant corresponding to wavelength λ_2. This represents the incremental change in power over a small segment dz. Over the entire length L of the fiber, this incremental modulation is attenuated by a factor of $e^{-\alpha(L-z)}$ due to fiber loss. The total modulation at the fiber's output is determined by integrating these contributions along the length of the fiber.

$$\int_0^L dP_2(z,\tau_2)e^{-\alpha(L-z)} \quad \text{(II.14)}$$

XPM crosstalk is assessed by normalizing it to the modulation magnitude, approximately $\lambda_1\approx mP_c\exp(-\alpha L)$. This normalized crosstalk is expressed using phasor notation as:

$$Xt_{XPM}=\frac{-2\Omega^2\gamma P_C\beta_2}{(\alpha-j\Omega d_{21})^2}(e^{-\alpha L}\cos(\Omega d_{21}L(-1+\alpha L))+j[e^{-\alpha L}\sin(\Omega d_{21}L)-\Omega d_{21}L]) \quad \text{(II.15)}$$

An analogous expression can be determined for the crosstalk at wavelength λ_1.

$$Xt_{XPM}=\frac{-2\Omega^2\gamma P_C\beta_1}{(\alpha-j\Omega d_{12})^2}(e^{-\alpha L}\cos(\Omega d_{12}L(-1+\alpha L))+j[e^{-\alpha L}\sin(\Omega d_{12}L)-\Omega d_{12}L]) \quad \text{(II.16)}$$

II.6.3 Four Wave Mixing (FWM)

Four-wave mixing is mitigated by non-zero dispersion-shifted fiber (NZDSF), now widely available. NZDSF achieves this by maintaining a small, non-zero dispersion in the EDFA transmission window. The third-order polarization concept is essential for comprehending its functionality.

$$P_{NL} = \varepsilon_0 \chi^{(3)} \vdots EEE \quad \text{(II.17)}$$

The induced nonlinear polarization (P_{NL}) in a material is related to the electric field (E) and the vacuum permittivity (ε_0) by equation (II.17). For four optical waves at frequencies ω_1, ω_2, ω_3, and ω_4, each linearly polarized along the x-axis, the total electric field is given by:

$$E = \frac{1}{2}\hat{x}\sum_{1}^{4} E_j \exp\left[i(k_j z - \omega_j t)\right] \quad \text{(II.18)}$$

For each of the four waves, the propagation constant is defined as $k_j = n_j\omega_j$=c, where n_j represents the refractive index. All waves are assumed to propagate in the same direction.

Substituting the expression for the total electric field (Equation (II.18)) into the equation for the nonlinear polarization (Equation (II.17)), and expressing P_{NL} in a similar form as E, yields:

$$P_{NL} = \frac{1}{2}\hat{x}\sum_{1}^{4} P_j \exp\left[i(k_j z - \omega_j t)\right] \quad \text{(II.19)}$$

Each nonlinear polarization component, P_j (j = 1 to 4), is found to contain many terms, each formed by the product of three electric fields. P_4, for example, can be expressed as:

$$P_4 = \frac{3\varepsilon_0}{4}\chi^{(3)}_{xxxx}\begin{bmatrix} |E_4|^2 E_4 + 2(|E_1|^2 + |E_2|^2 + |E_3|^2)E_4 \\ +2E_1E_2E_3\exp(i\theta_+) \\ +2E_1E_2E_3^*\exp(i\theta_-) + \ldots \end{bmatrix} \quad \text{(II.20)}$$

where the definitions of θ_+ and θ_- are given below:

$$\begin{cases} \theta_+ = (k_1 + k_2 + k_3 - k_4)z - (\omega_1 + \omega_2 + \omega_3 - \omega_4)t \\ \theta_- = (k_1 + k_2 - k_3 - k_4)z - (\omega_1 + \omega_2 - \omega_3 - \omega_4)t \end{cases} \quad \text{(II.21)}$$

In Equation (II.20), the first four terms involving E_4 are responsible for self-phase modulation and cross-phase modulation. The remaining terms arise from four-wave mixing . There are two types of FWM terms. The term with θ_+ corresponds to three photons combining to create a single photon at $\omega_4 = \omega_1 + \omega_2 + \omega_3$. This leads to phenomena like third-harmonic generation ($\omega_1 = \omega_2 = \omega_3$) or frequency conversion ($\omega_1 = \omega_2 \neq \omega_3$). Phase matching for these processes is generally difficult in optical fibers. The term with θ_- corresponds to the annihilation of two photons (ω_1 and ω_2) and the simultaneous creation of two photons (ω_3 and ω_4), such that [39]:

$$\omega_3 + \omega_4 = \omega_1 + \omega_2 \quad \text{(II.22)}$$

II.7 Conclusion

This chapter explores the evolution of wavelength division multiplexing and its evolution towards spectrally efficient systems like Nyquist-WDM. DWDM systems have expanded optical network capacities but face limitations in spectral efficiency and inter-channel interference. Nyquist-WDM uses the Nyquist criterion for pulse shaping, enabling minimal interference and higher data rates within limited bandwidths. Even though it is more complicated to set up and can be affected by certain distortions, Nyquist-WDM provides better use of available bandwidth and is a strong option for future high-capacity optical networks. The mathematical modeling presented in this chapter further reinforces the importance of understanding fiber nonlinearities and their impact on system performance.

Chapter III:
Simulation of advanced Nyquist WDM systems

General conclusion

General conclusion

This research aimed to simulate and analyze advanced Wavelength Division Multiplexing (WDM) systems, with a focus on understanding the capabilities and trade-offs of coherent WDM and Nyquist-WDM technologies. As optical networks face increasing demand for capacity and spectral efficiency, the study evaluated how these modern techniques meet such requirements.

In **Chapter I**, we established the fundamentals of coherent WDM systems, highlighting their advantages—such as improved sensitivity, advanced modulation support (e.g., DP-16QAM), and powerful digital signal processing (DSP) to counteract impairments like chromatic dispersion and nonlinearities. Key system components and operational challenges were also reviewed.

Chapter II explored Nyquist-WDM in comparison with conventional Dense WDM (DWDM). By applying Nyquist pulse shaping, Nyquist-WDM achieves tighter channel spacing with minimal crosstalk, greatly enhancing spectral efficiency. The chapter detailed technical advantages, such as reduced interference and higher channel density, alongside implementation challenges like filter precision and synchronization demands.

In **Chapter III**, we conducted numerical simulations across various scenarios to evaluate the performance of DWDM and Nyquist-WDM. Variables such as input power, channel spacing (100 GHz to 33 GHz), bit rates (14–28 Gbaud), and fiber length were tested. Performance was measured using BER, OSNR, and Q-factor, providing a comparative view of system behavior. Results confirmed that Nyquist-WDM offers superior spectral utilization while coherent detection and DSP are critical for system optimization.

Overall, the study confirms that Nyquist-WDM combined with coherent detection provides a promising solution for meeting the growing capacity demands of optical communication systems. While it introduces some complexity, the trade-off is justified by improved efficiency and performance.

Future directions include exploring machine learning techniques for DSP optimization, which may reduce complexity while enhancing adaptability. Additionally, extending the study to higher-order modulation formats and denser multiplexing strategies could further increase system capacity, though these would require addressing additional challenges related to signal integrity and processing demands.

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Appendix

Appendix

As part of the academic requirements for completing my degree, I had the opportunity to carry out a professional internship within the Information Technology (IT) Department of the SONATRACH-ENI-MLE Group, located in Hassi Messaoud. This internship provided me with a valuable opportunity to apply the theoretical knowledge acquired throughout my studies in a real-world, industrial environment.

Sonatrach ENI-MLE is one of the key players in the energy sector in Algeria. It is the result of a strategic partnership between the national company Sonatrach and the Italian company ENI-MLE. This joint venture operates in exploration, production, transportation, and processing, with a strong focus on modernizing its infrastructure and developing information and communication systems to support its industrial operations and ensure the safety and security of vital installations.

I had the valuable opportunity to complete my practical internship within the Information Technology (IT) Department of the group. Through this internship, I aimed to enhance my academic knowledge by engaging directly with a real work environment. This department is responsible for overseeing digital networks, communication systems, security cameras, and modern technologies related to IT infrastructure. It places particular emphasis on optical communication technologies (Fiber Optics), which have become the backbone of digital transmission systems in major institutions.

In this report, I will present a summary of what I have learned during the internship period, highlighting the practical aspects and skills I acquired, and demonstrating the link between theoretical training and field experience.

The following images illustrate some of the key components and equipment I worked with, providing a visual overview of the practical experience I gained throughout the training period.

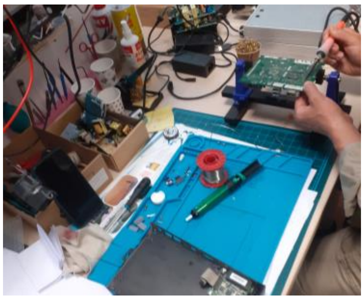
A.1: Fiber Optic Cables and Splicing Work

A.2: Surveillance Camera – ULISSE COMPACT

A.3: Professional Display and TV Receiver Setup

A.4:TV control room

A.5:1000BASE-BX10-D/U SFP Module



A.6: Electronic Repair through Soldering Work

A.7: Electrical control room

A.8: Central Processing Facility (CPF)

A.9: Oil Well Site

This A.1 illustrates the critical process of fiber optic cable splicing, a fundamental task in modern telecommunication infrastructure. Fiber splicing ensures seamless transmission of light signals across long distances with minimal loss. During the internship, I learned how to prepare, align, and fuse optical fibers using specialized equipment. This process is essential for maintaining high-speed data connections, whether in local area networks or wide-scale industrial systems.

The ULISSE COMPACT camera shown in A.2, is a high-performance surveillance device used in industrial security systems. Manufactured by Videotec (Italy), this model is equipped with advanced night vision capabilities and remote-control features. Through field exposure, I gained hands-on experience in the installation and positioning of such cameras, as well as understanding their role in real-time monitoring and ensuring facility safety.

The A.3 show the professional-grade Philips display and a receiver unit designed for centralized television broadcasting in corporate environments. These systems allow full administrative control over content, channel selection, and viewing monitoring — features Often used for security. I participated in configuring the signal paths, power connections, and control interfaces between the screens and their receivers.

This device serves as the central unit responsible for managing the internal broadcast of TV channels within the company's facilities, the A.4. It allows administrators to define the available channels, monitor content, and control what is displayed on screens across the organization. This system plays a vital role in ensuring that only authorized content is shown, contributing to organizational security and professional control of internal media.

Here we see a 1000BASE-BX10-D/U SFP (Small Form-factor Pluggable) transceiver, A.5. This type of module is used for high-speed bidirectional communication over a single fiber using different wavelengths for upstream and downstream data. I became familiar with various SFP modules during the internship and learned how to identify and connect them within network switches and routers — key components in any fiber optic infrastructure.

During my internship, I took part in repairing a television receiver that failed after over seven years of use, A.6. After careful inspection, four capacitors were found had burned out due to aging. Using a soldering iron, we replaced them with new components, successfully restoring the device. This experience enhanced my practical skills and gave me deeper insight into the internal workings of electronic systems.

Electrical rooms connected via fiber optic lines form a distributed but centralized control system, A.7 This setup allows real-time data transmission and coordination between different power management units across the facility. I learned how fiber is used not only for internet and communication but also as a backbone for linking critical energy systems, allowing enhanced monitoring and automation of electrical infrastructure.

The Central Processing Facility (CPF) is a vital part of the oil production chain, responsible for processing the raw fluids extracted from wells, A.8. It separates and treats these fluids to produce marketable gas, oil, condensate, and LPG, all in accordance with industry specifications. The facility includes advanced systems for gas pretreatment, impurity removal (such as H_2S and CO_2), dehydration, cooling, compression, and stabilization. Additionally, it features specialized units for the storage and pumping of the final products, as well as essential service systems like heating, drainage, water treatment, and safety flare systems, ensuring efficient and secure operations.

The A.9 represents one of the oil production or drilling sites managed by the company. This site highlights the connection between industrial field operations and IT infrastructure, where technologies such as fiber optics, security systems, and remote monitoring tools are deployed to ensure operational efficiency, safety, and real-time data access in remote and demanding environments.

This internship at the Information and Communication Technology (IT) Department of SONATRACH ENI-MLE was not just a technical training period, but a deeply enriching experience that left a lasting mark on both my academic and personal journey.

Through direct field involvement, I didn't only learn about fiber optic splicing, surveillance systems, or server setup I gained a deeper understanding of discipline, teamwork, and the true value of responsibility within a real professional environment. I witnessed how theoretical knowledge acquired at university transforms into practical, hands-on work in a large-scale, efficiently managed industrial setting.

I was genuinely touched by the spirit of collaboration within the technical team and the sincere willingness of engineers and supervisors to share their knowledge and guide me. I felt a real sense of belonging as if I were an integral part of a system striving to ensure secure communication, safeguard infrastructure, and support the digital backbone of one of the country's key economic pillars.

This internship not only enhanced my technical skills but also solidified my work ethic and aspirations. It opened my eyes to the vast opportunities that lie ahead, fueled by what I have learned and achieved through this invaluable experience.